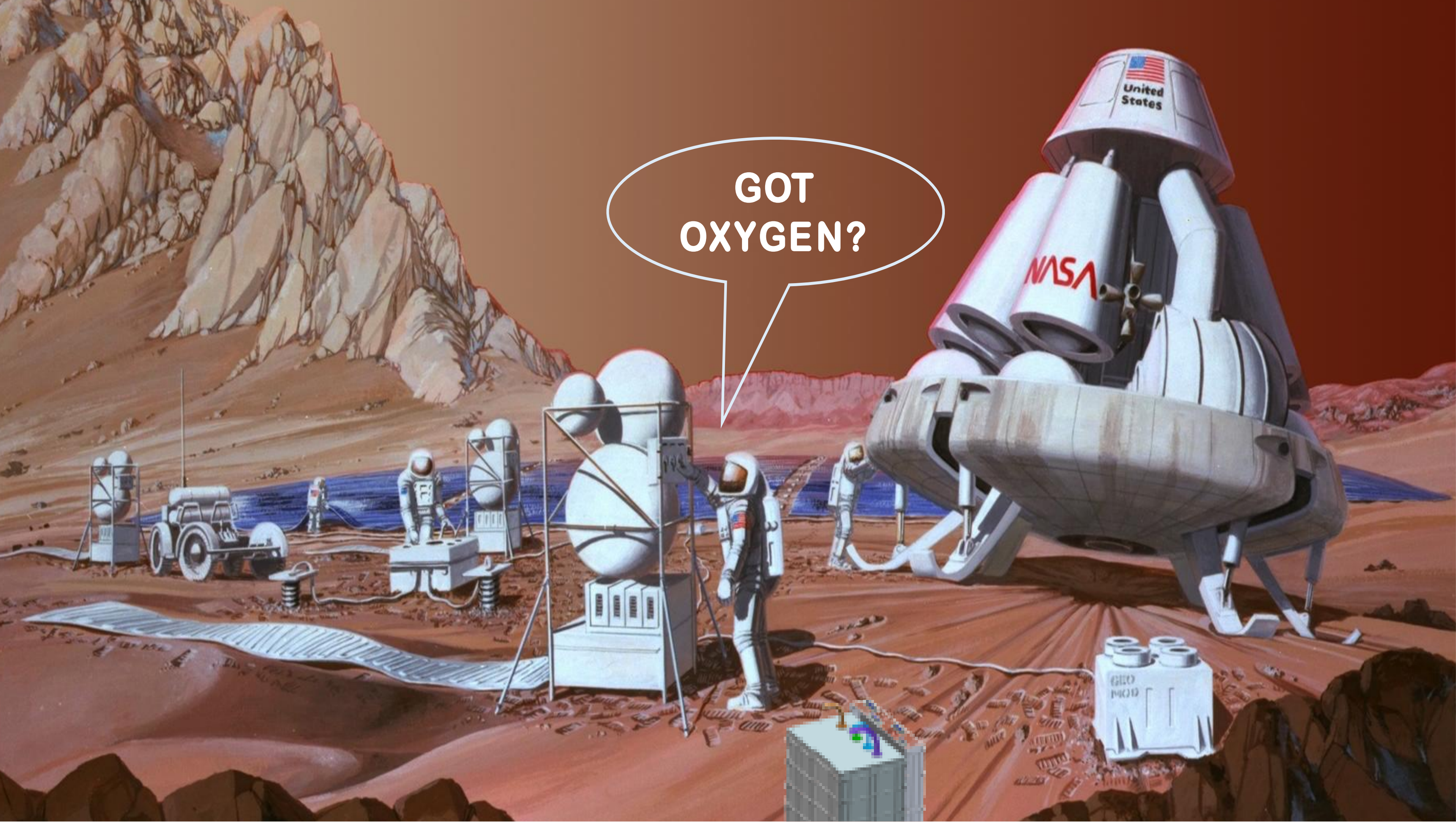

MOXIE: Generating Oxygen On Mars

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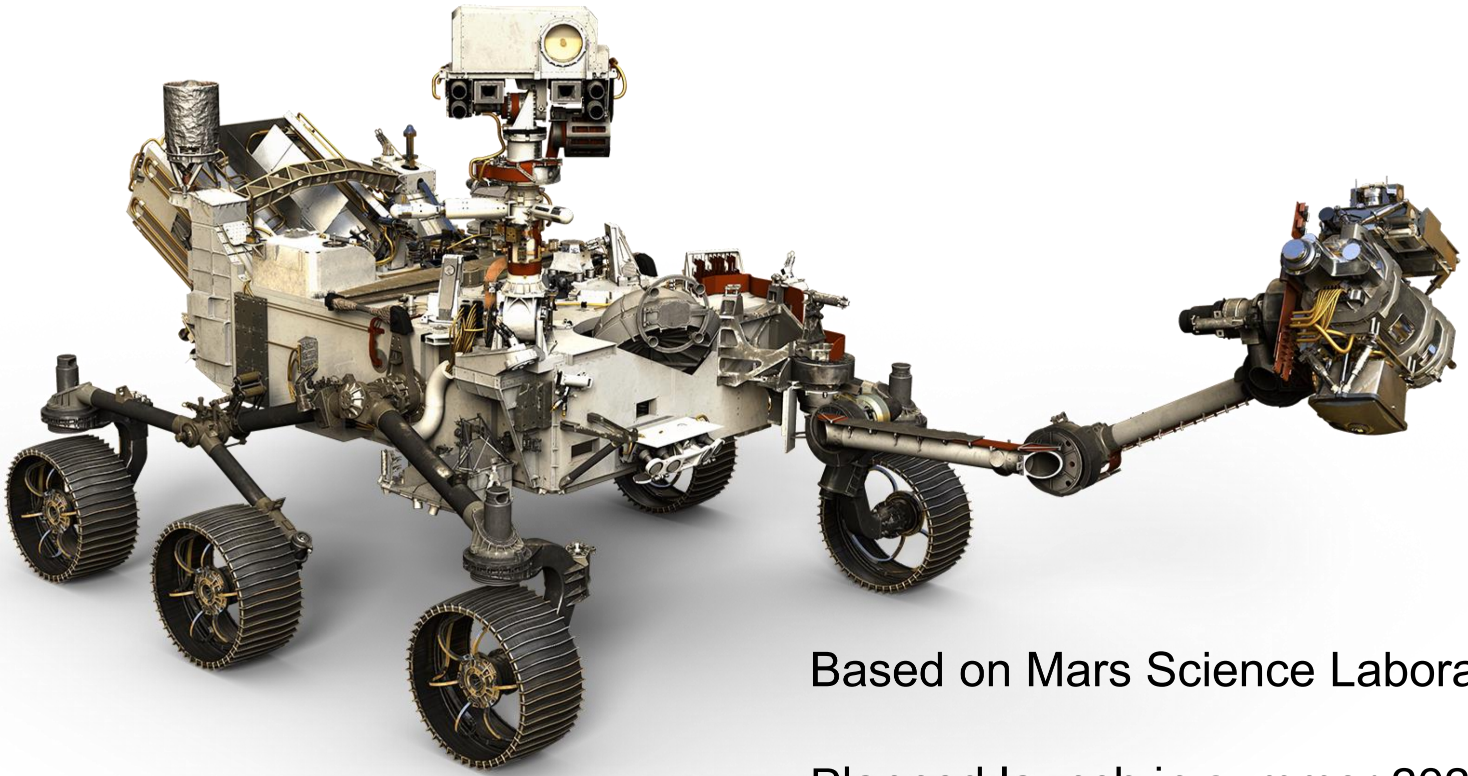
Thermal Systems Engineer
Instrument and Payload Thermal Engineering (353F)
September 18, 2017

Jet Propulsion Laboratory
California Institute of Technology

Outline

- Mars2020 and ISRU
- MOXIE
- MOXIE hardware implementation and technical challenges
- The future…

Mars2020



Based on Mars Science Laboratory ("Curiosity")

Planned launch in summer 2020

Science goals:
- Looking for Past Habitability
- Seeking Biosignatures
- Caching Samples
- **Preparing for Humans**

ISRU: “Living off the land”

ISRU: In-situ Resource Utilization -- Using the resources available where you are to make useful things

Goal: Avoid having to bring everything from Earth (drives launch mass)

Possible usable resources in solar system:

- Minerals from Moon: raw materials, oxygen
- Water (ice) from asteroids/comets
- Gases from gas giants

ISRU on Mars

Resources on Martian surface:

- Rocks
- Dust
- More dust
- Water (ice caps, underground?)
- Mars rovers/landers
- **CO_2**
  - Atmosphere: 95% CO_2, ~3% N_2, ~2% Ar
  - Low density: ~1/100 Earth pressure (2-12 torr, average ~7 torr)

What can we do with CO_2?

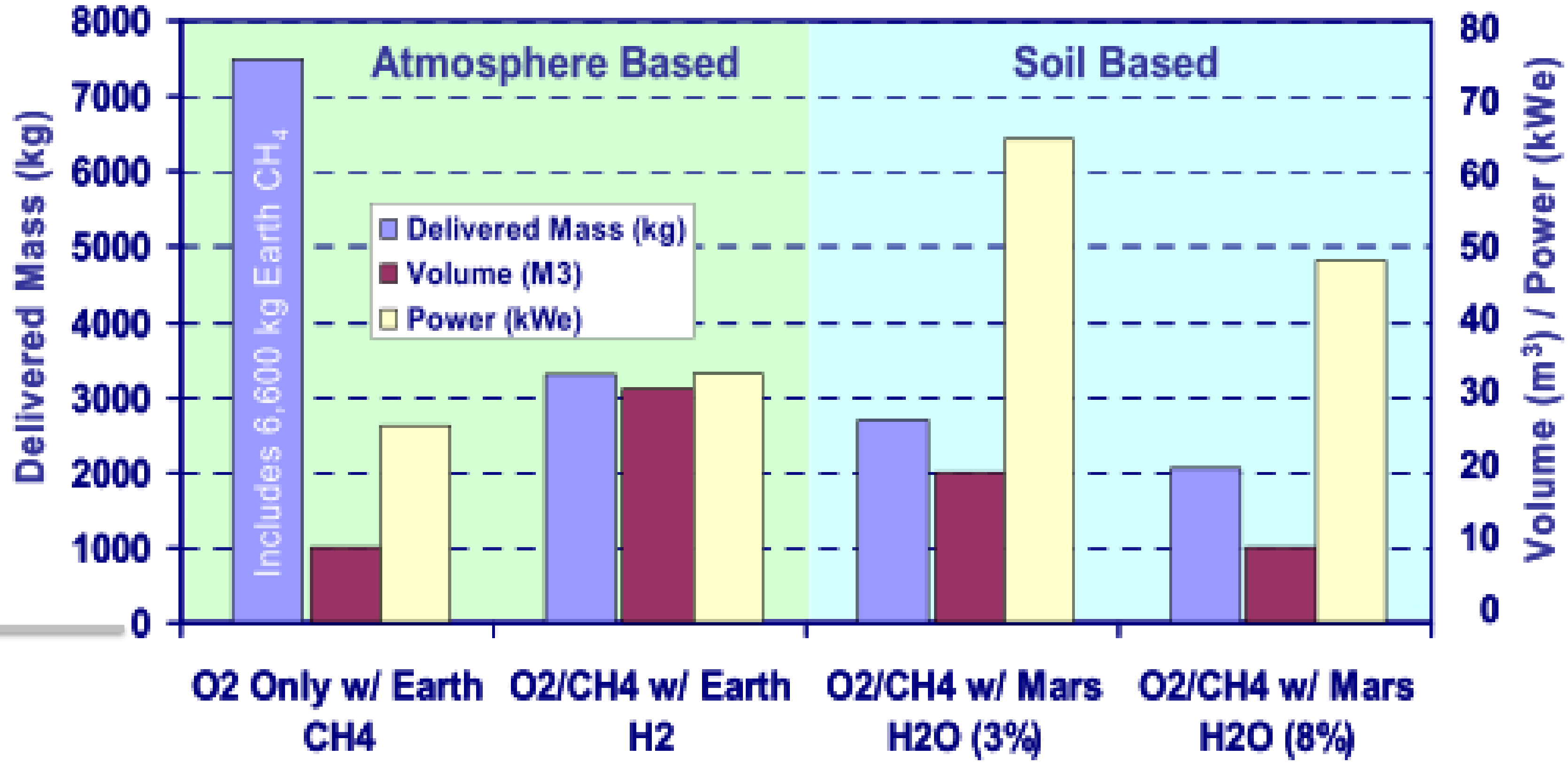
- CO_2 has O_2, and O_2 is useful – breathing, **oxidizer**
  - Mars ascent requires ~35 metric tons oxygen
  - Requires launching ~200 metric tons from Earth

- What if we could make O_2 on Mars?

ISRU on Mars: Human-scale

Without ISRU (~35,000 kg)

Simplest



Drake 2009

MOXIE: The Mars Oxygen ISRU Experiment

- Goal: demonstrate the production of oxygen (O_2) from Mars CO_2 atmosphere
- PI: Michael Hecht, MIT Haystack Lab
  - Deputy PI: Jeff Hoffman, MIT AeroAstro
- Project Management and implementation: JPL
- MOXIE is a NASA “Class D” instrument: lower cost, higher risk tolerance, ideal for new technology infusion

- Supported by HEO/AES, STMD/Tech Demos
- Mars 2020 Project managed by SMD

Why send MOXIE to Mars?

- Reduce risk/mature the technology *for flight*
- Inform future designs / Learn how to scale up
- Send a message to an interested & enthusiastic public

Public engagement

SECTIONS HOME SEARCH

The New York Times

SPACE & COSMOS

NASA to Test Making Oxygen, Key to Rocket Fuel, on Mars

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SPACE

Next Mars Rover Will Make Oxygen from CO2

The spacecraft, due in 2020, will have a reverse fuel cell to produc
to breathe

NASA's next Mars rover will make oxygen, look for farmland

By Ben Brumfield, CNN
Updated 11:11 AM ET, Sun August 3, 2014

New Scientist

HOME NEWS TECHNOLOGY SPACE PHYSICS HEALTH EARTH HUMANS LIFE TOPICS EVENTS

DAILY NEWS 31 July 2014

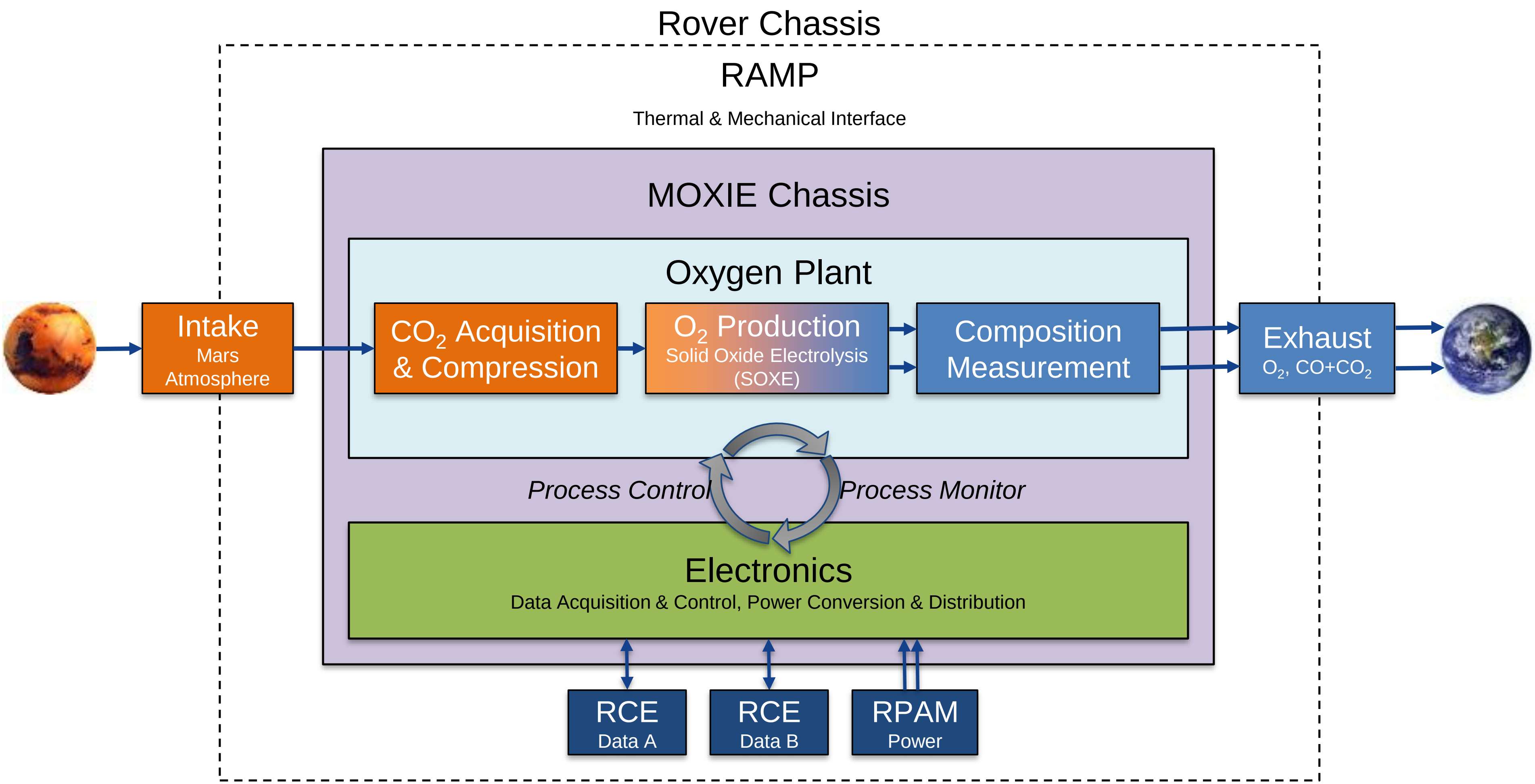
Next rover will pull oxygen from Martian air

By Lisa Grossman

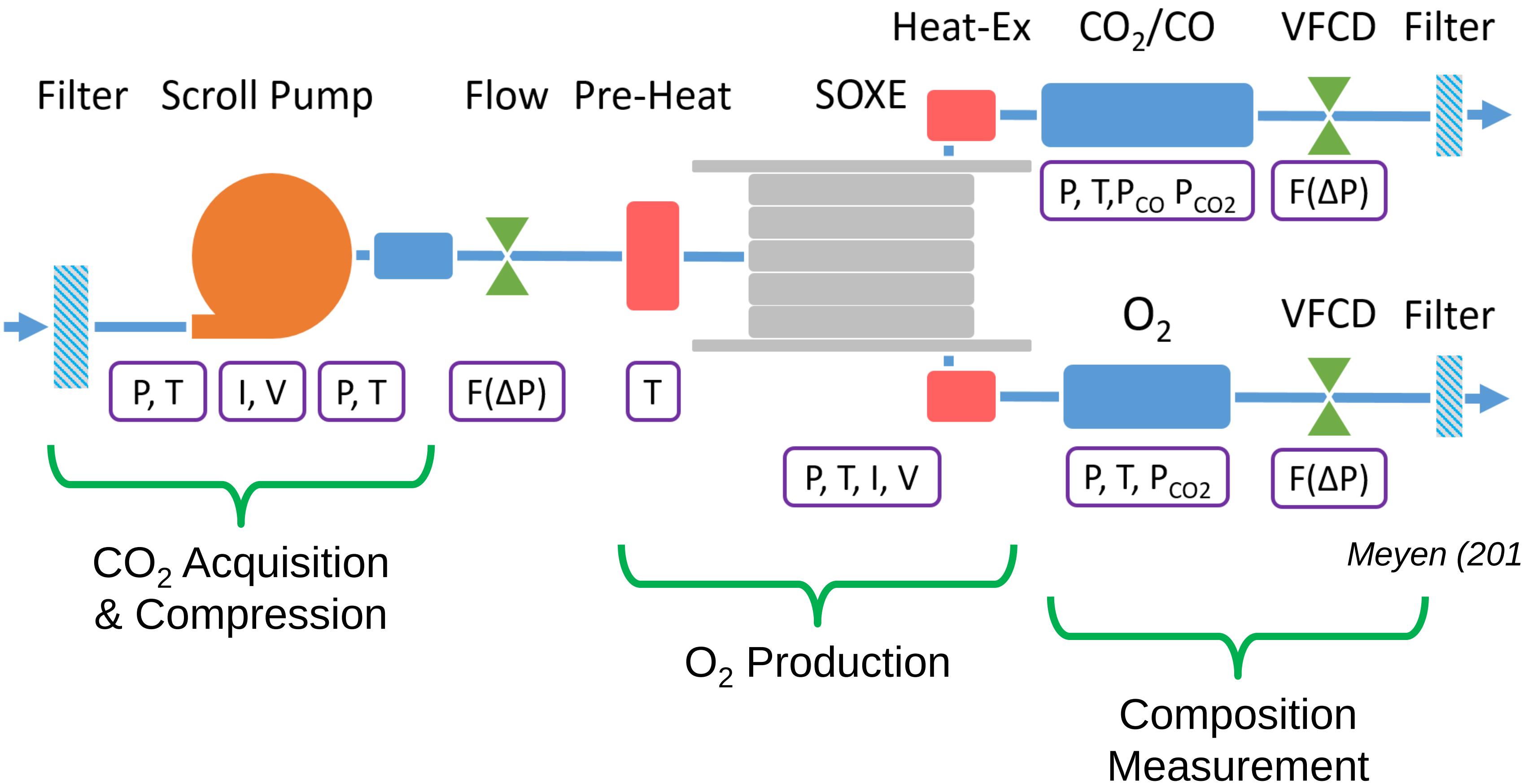
MOXIE Top-level requirements

- Generate oxygen on Mars – minimum 6g/hr at 5 torr / 0° C environment
- Produce oxygen at >98% purity
- Operate at least 10 times in various environmental conditions over Mars2020 mission life (1.5 Mars years)

MOXIE System Block Diagram



MOXIE System Block Diagram

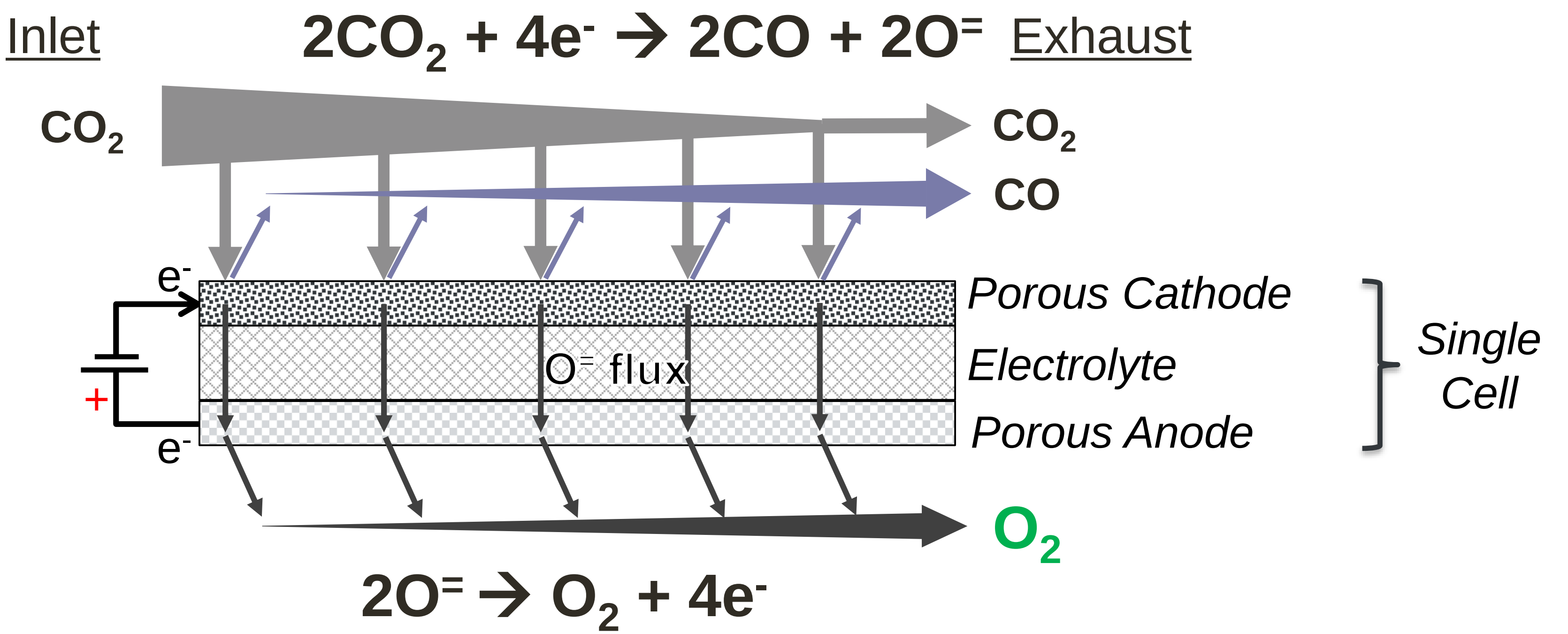


Meyen (2015)

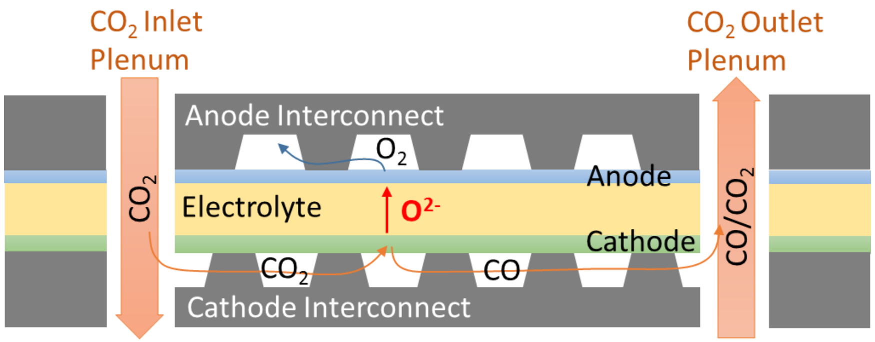
Solid Oxide Electrolysis

"Reverse Fuel Cell"

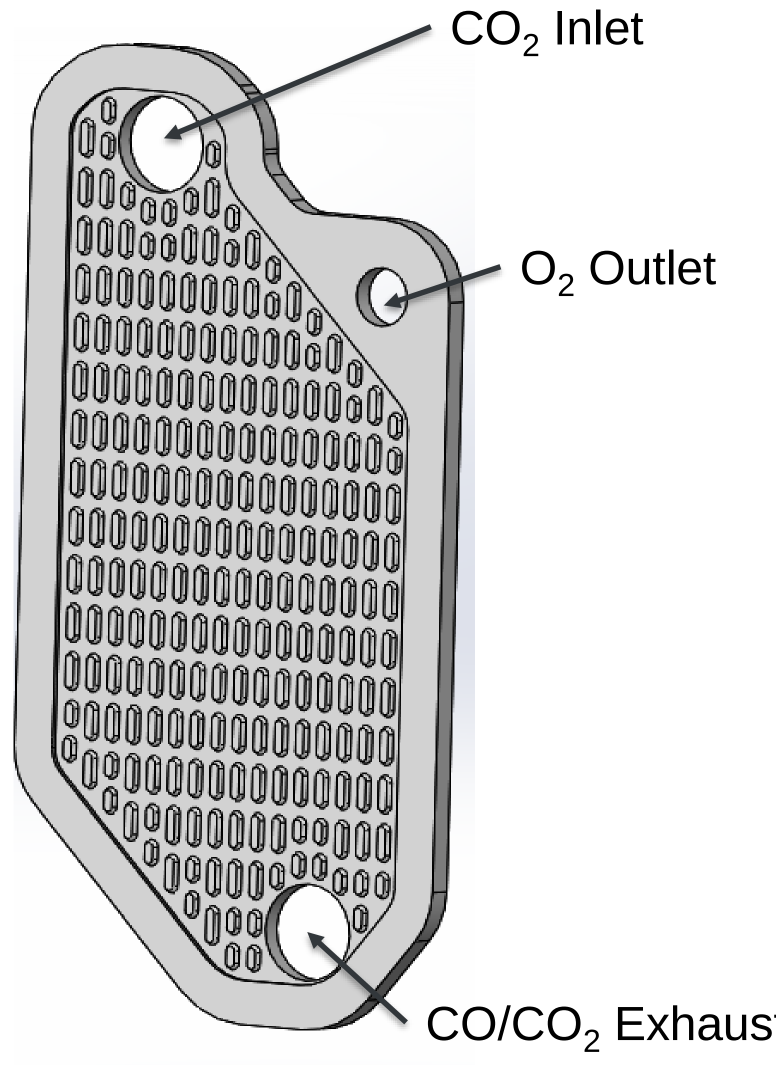
Doped ceramic (yttria-stabilized zirconia) conducts O_2 ions at high temp



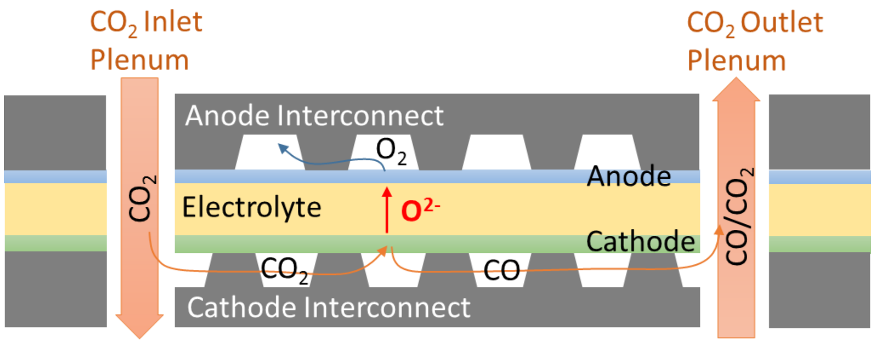
Solid Oxide Electrolysis – connecting cells

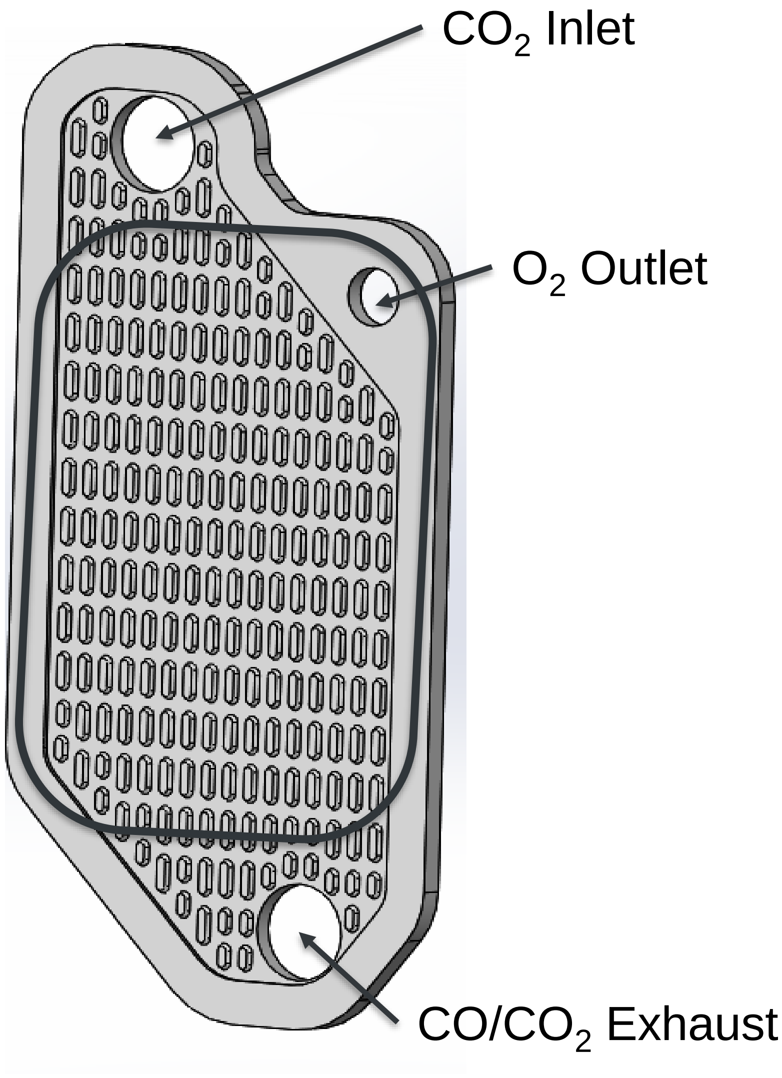


- High chromium alloy (matched CTE to ceramic electrolyte)
- Approximately 100mm x 50mm x 2mm
- Contains manifolding for gas streams

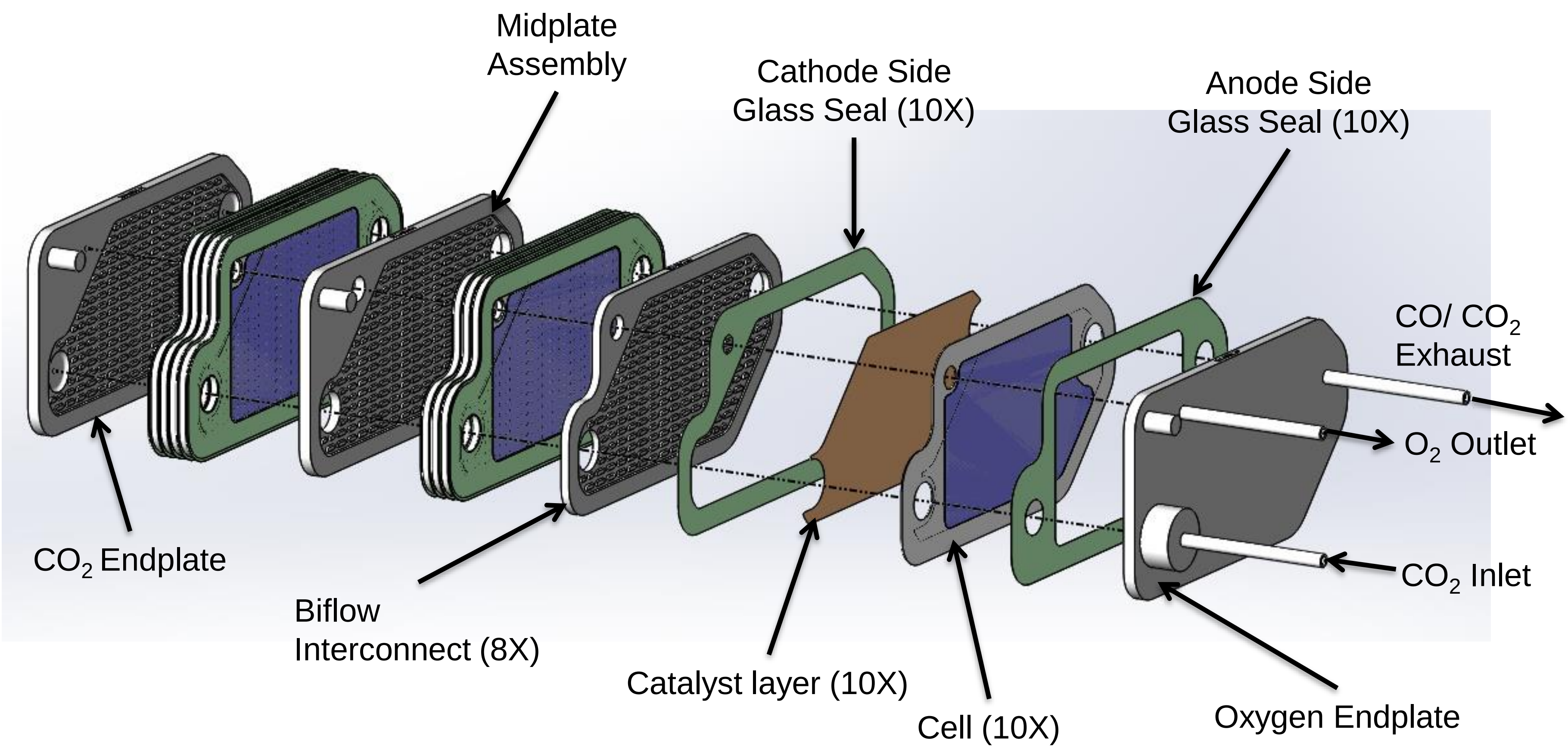


SOXE – connecting cells





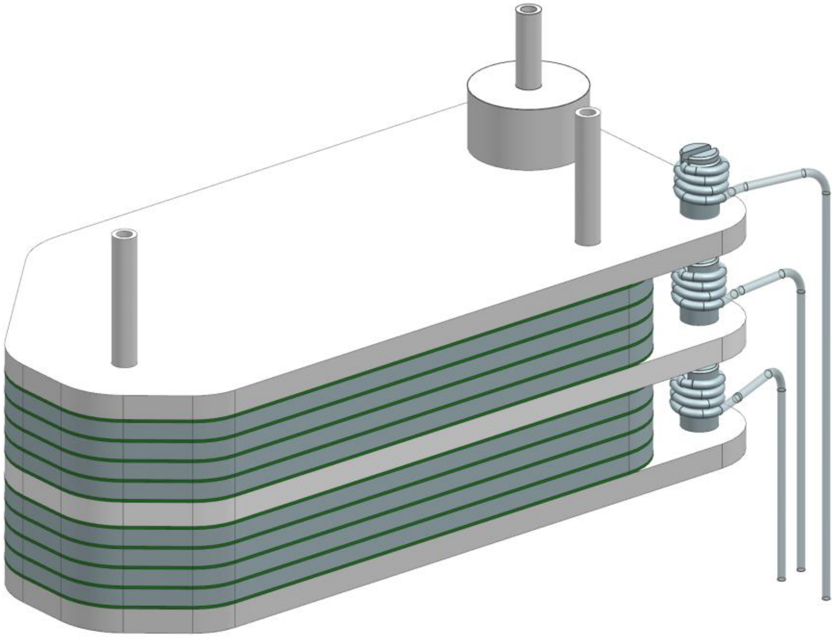
SOXE stack components

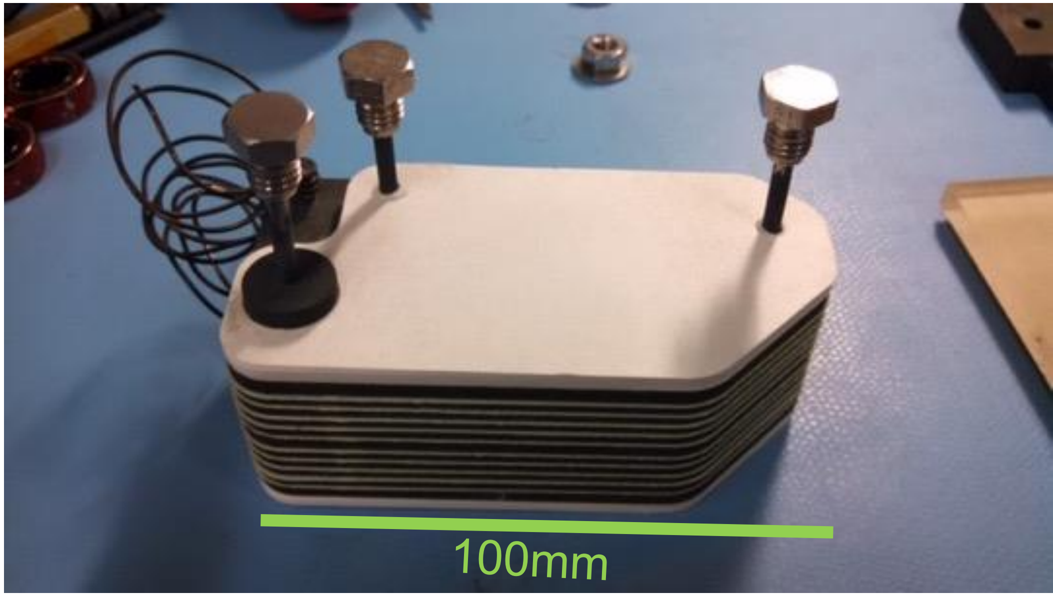


SOXE stack

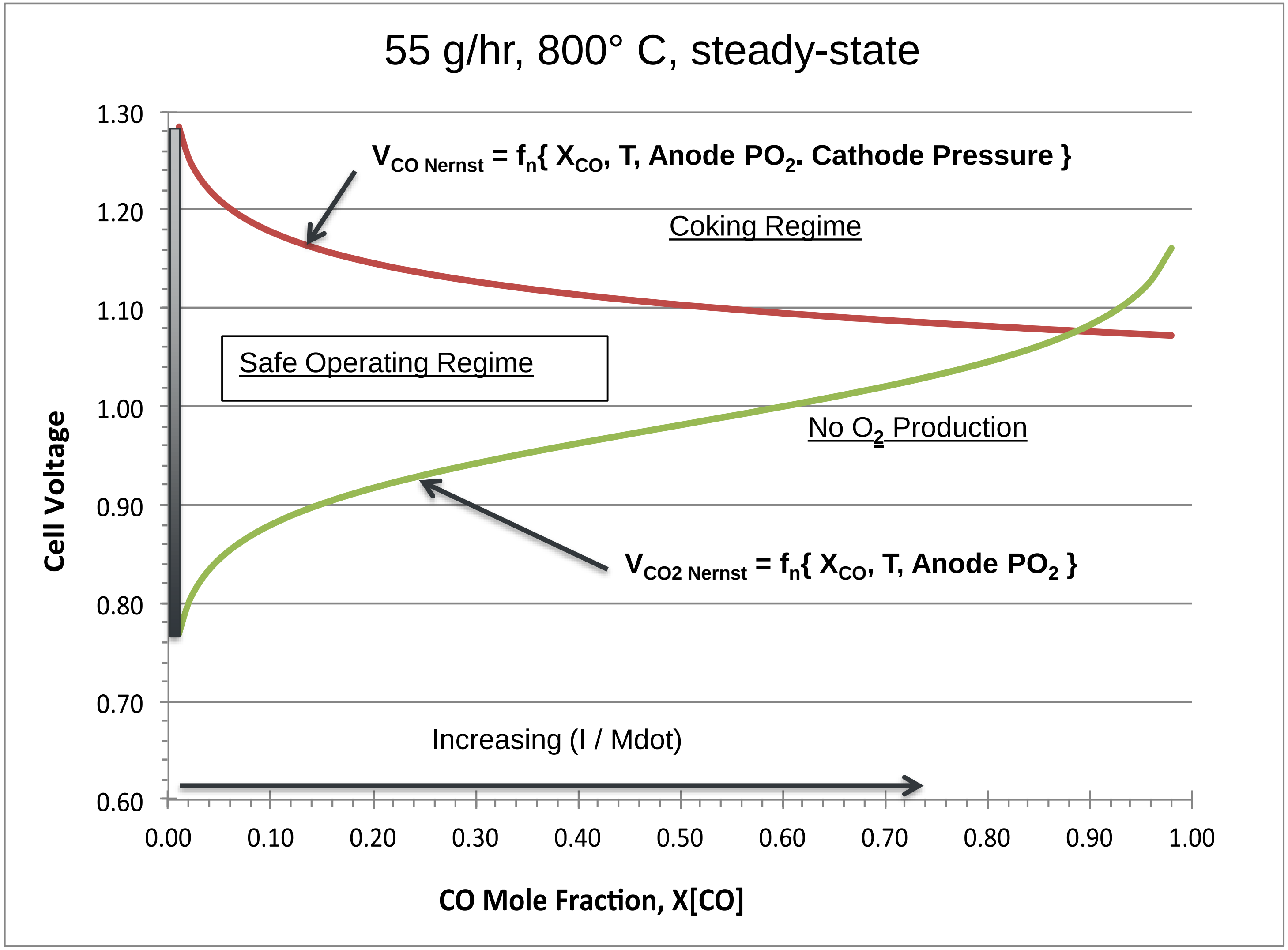
- Solid Oxide Electrolysis Units ("stacks")
- Configured as two electrically independent stacks of 5 cells each
- Cells, Interconnects, and End/Midplates held together by glass seals
- Inconel supply tubing and electrical leads
- Operating temperature of 800°C
- 6 g/hr O_2 out requires ~50 g/hr CO_2 in

- Stacks built and provided by partner Ceramatec, Inc. (now Oxeon Energy)

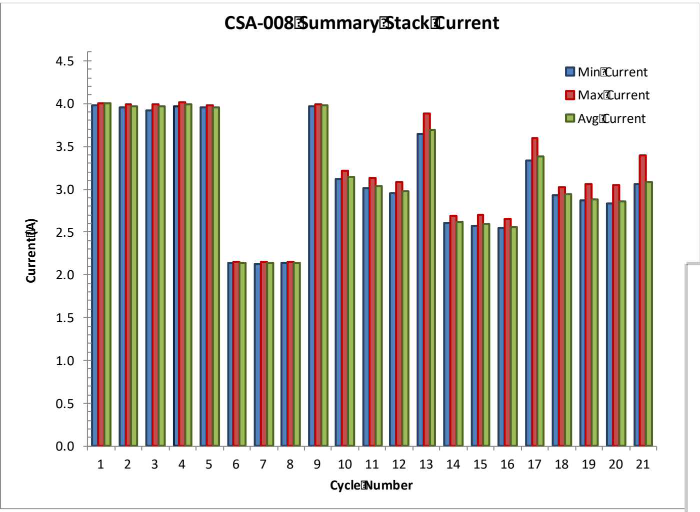


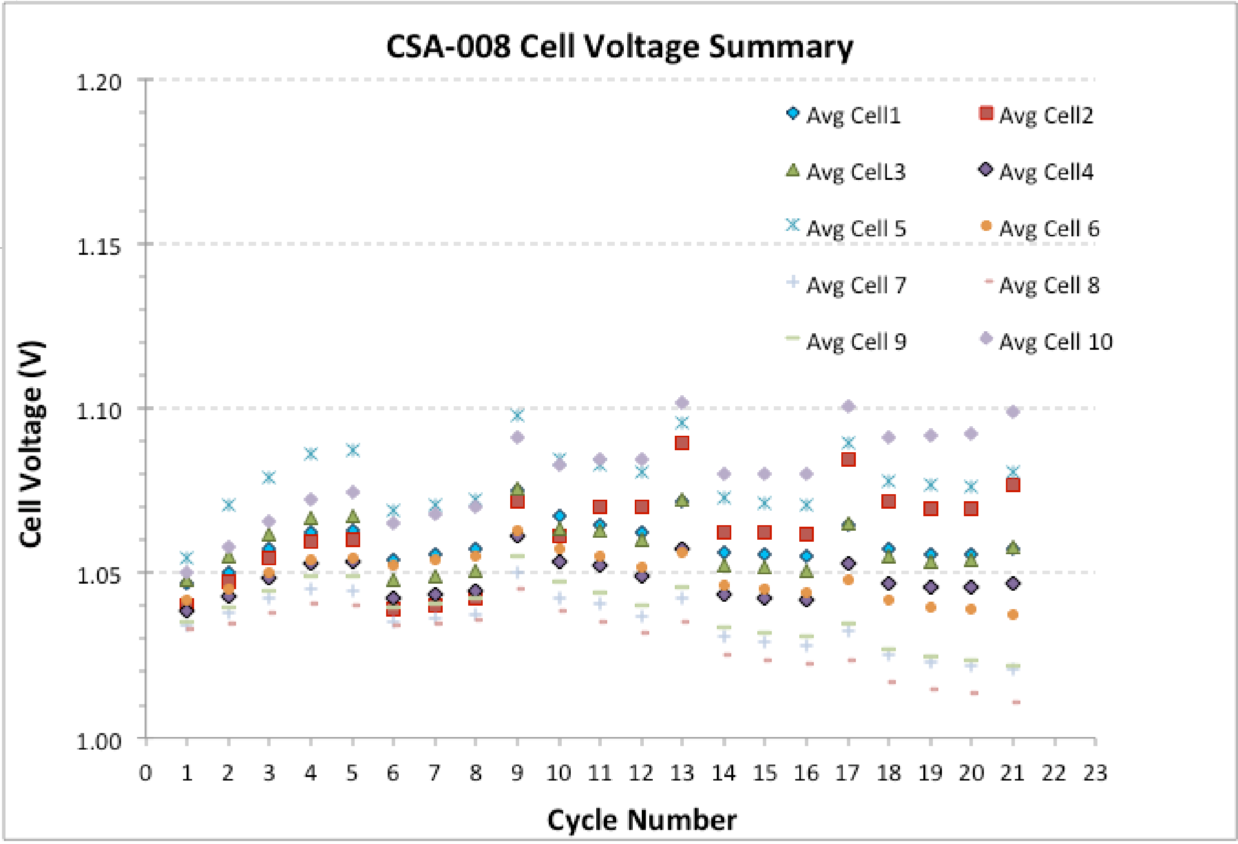


SOXE stack operating envelope



Cycle-to-Cycle Degradation





SOXE Performance

- Generate oxygen on Mars – minimum 6g/hr at 5 torr / 0° C environment: >1g/hr per cell (10 cells)
- Produce oxygen at >98% purity: All recent stacks exceed 99.9%
- Operate at least 10 times in various environmental conditions over Mars2020 mission life (1.5 Mars years): >45 cycles w/ no failures
- Oxygen production limited by:
  - Inlet flow (pump capacity, gas density at landing site)
  - Available power (4A limit, equiv. to 12 g/hr)
  - SOXE capability (10 cells, 22.7 cm^2/cell)

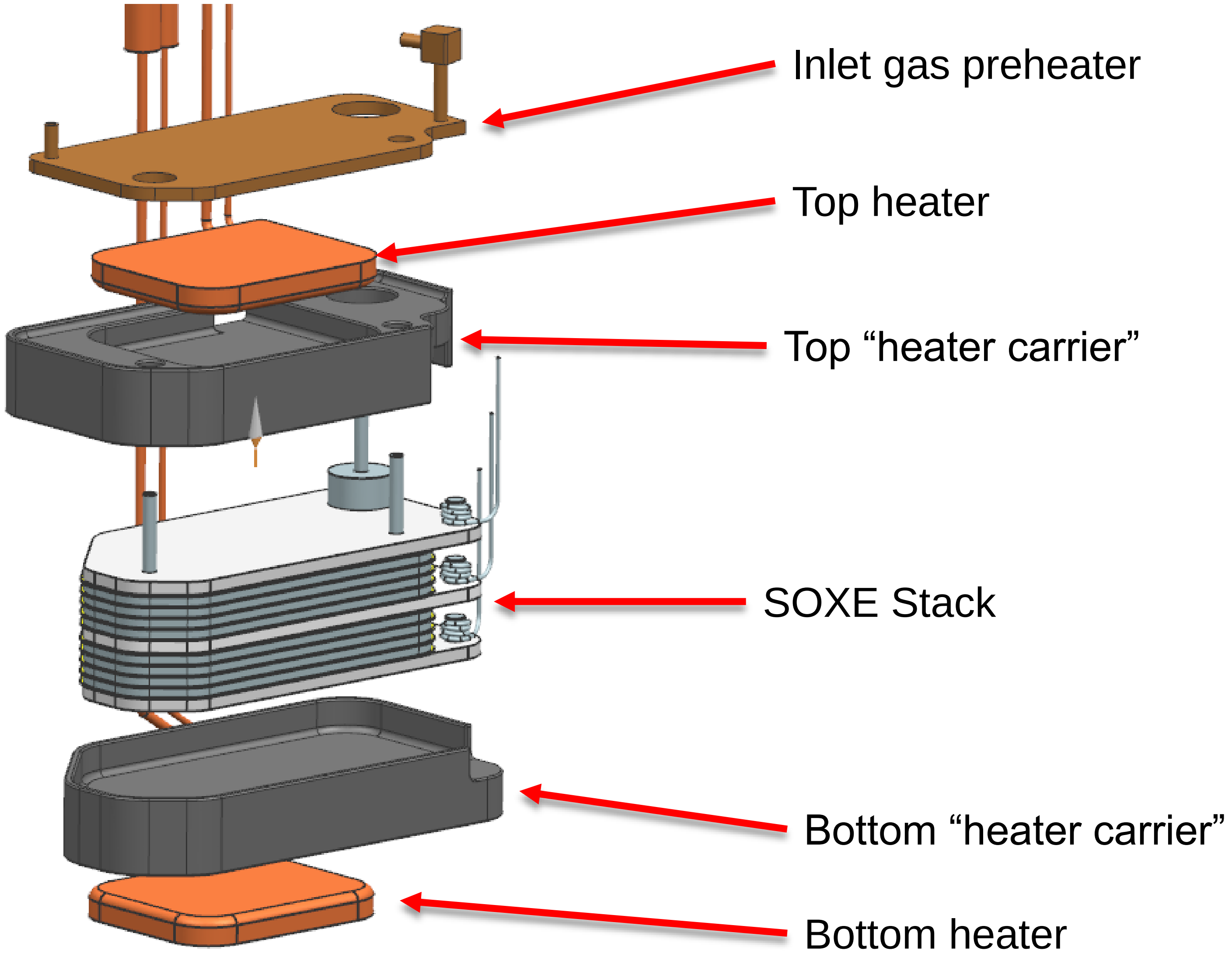
SOXE Packaging

- Package SOXE stack, SOXE heaters, and inlet gas heat exchanger
- Maintain at 800° C with < 70 W heater power
- Minimize total energy ($m\ C_p\ \Delta T$) required for warmup

- …and it all has to survive launch environments (concern: brittle ceramics in SOXE)

- …and provide mechanical compression along stack axis: 800 to 4000 N (180 to 900 lb)

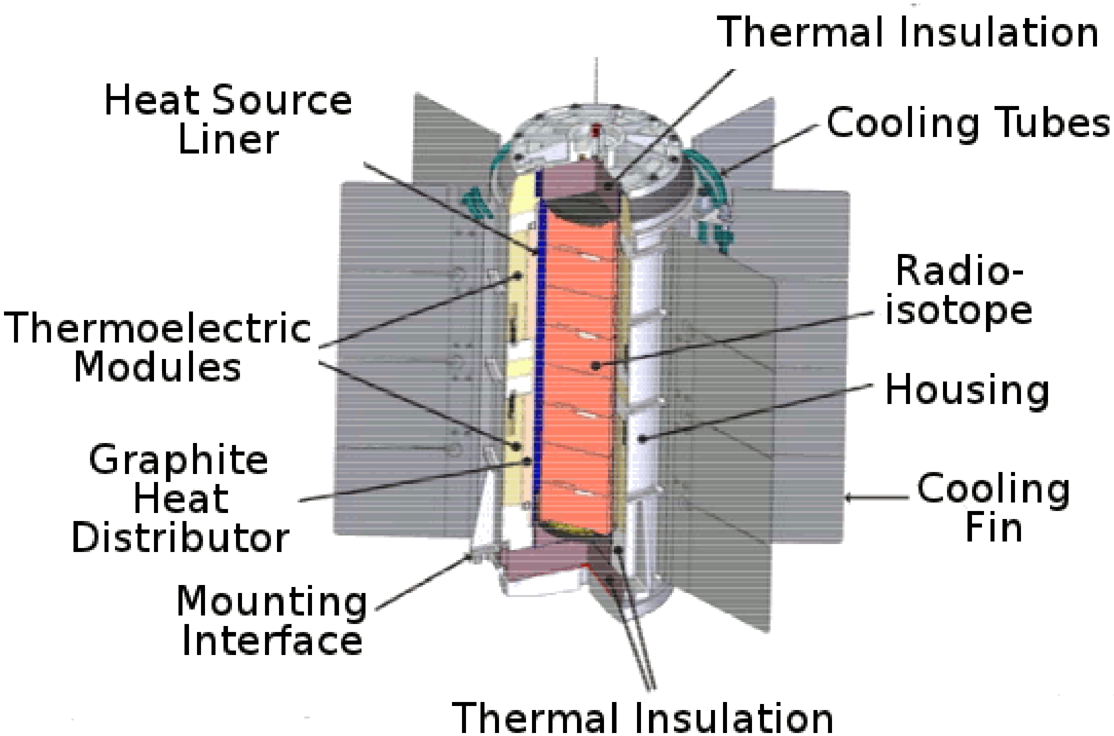
SOXE Assembly



Stack compression

- Evaluated various options (cold springs, hot springs, compress through insulation)
- Compressing through insulation – lowest mass, lowest energy
- Requires *structural* insulation – must be able to withstand full compressive loads

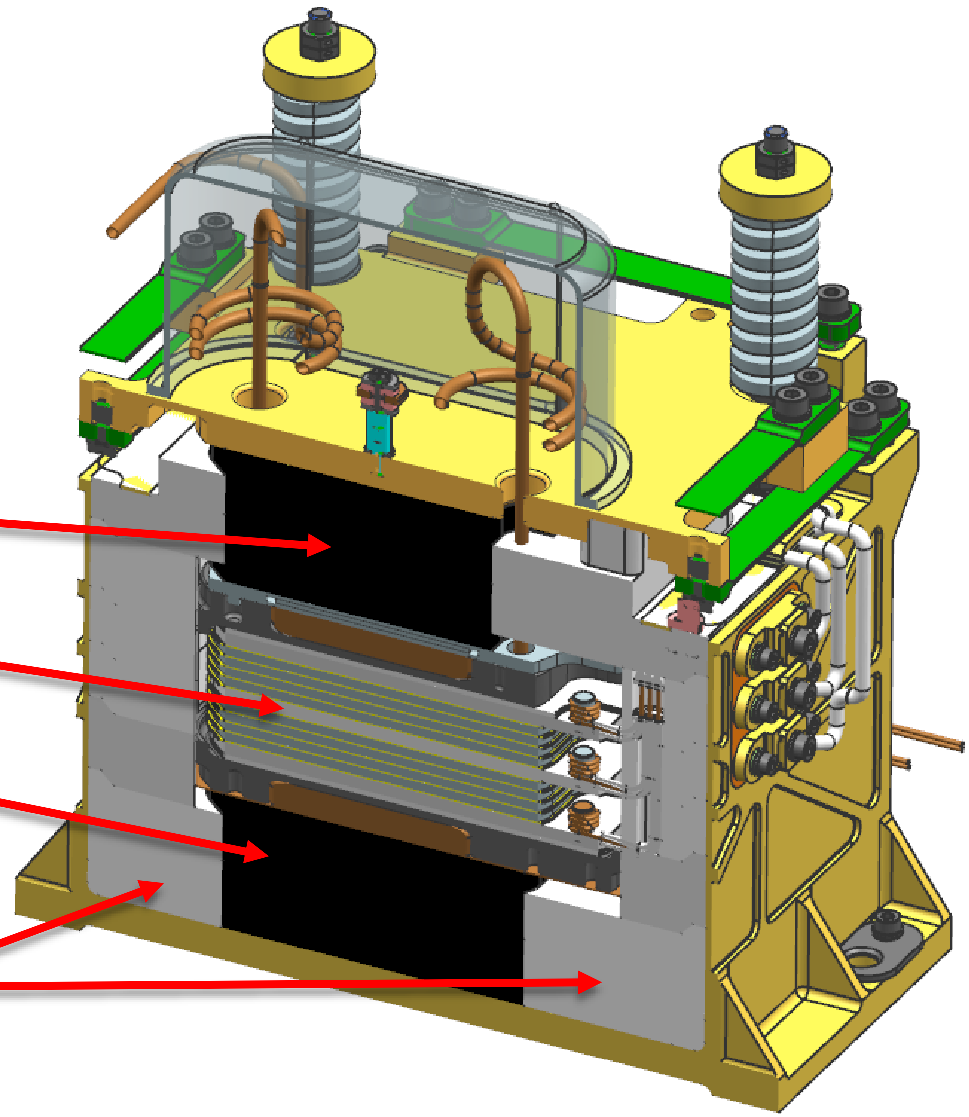
- Key concept: *Heritage*
  - Use insulation (Min-K) implemented in MMRTG
  - Low conductivity, sufficient strength
  - Issue: Min-K slowly relaxes with time, *especially at high temperatures*



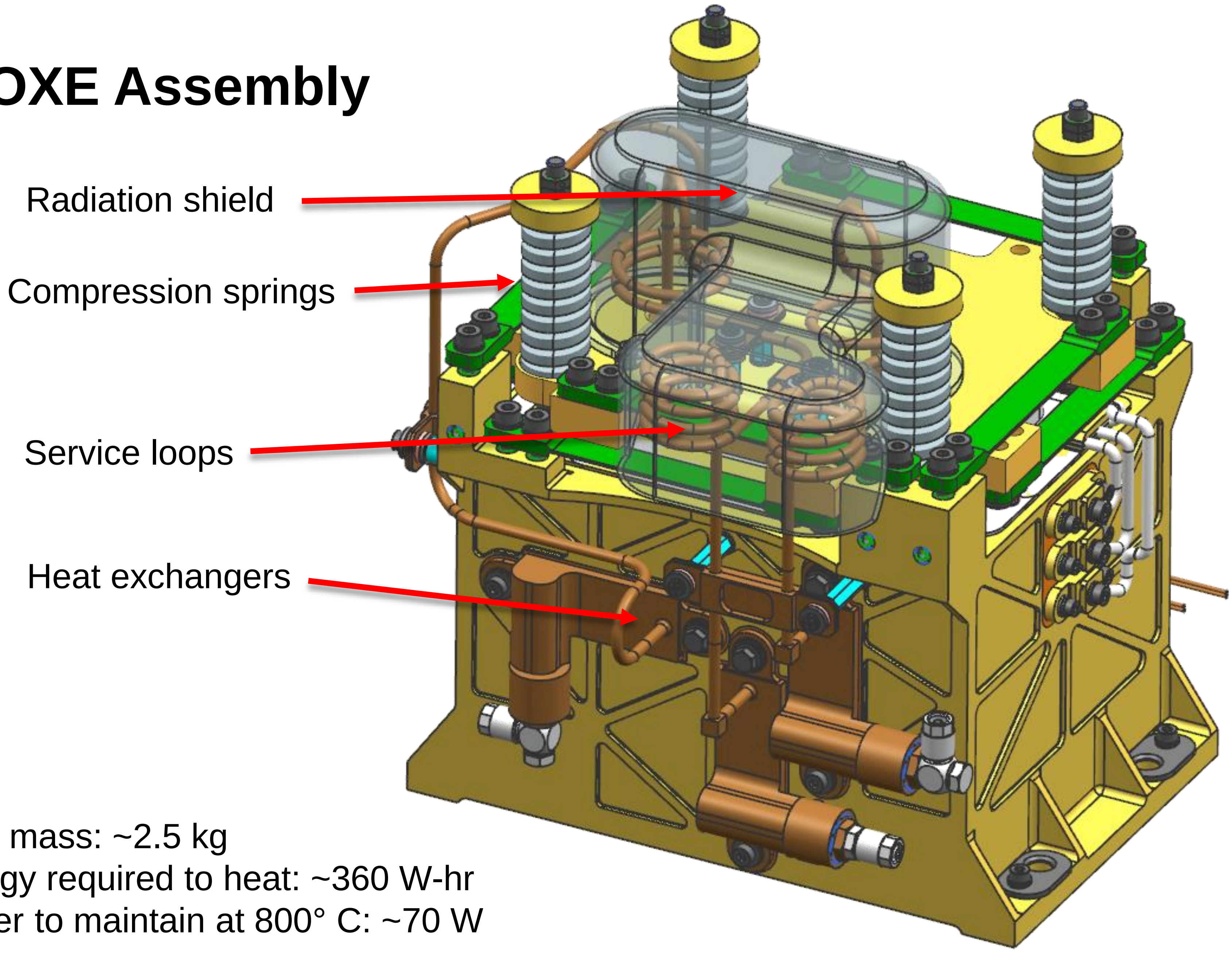
SOXE Assembly

Stack held in place via friction

~3000 N (~600 lbf) preload at launch

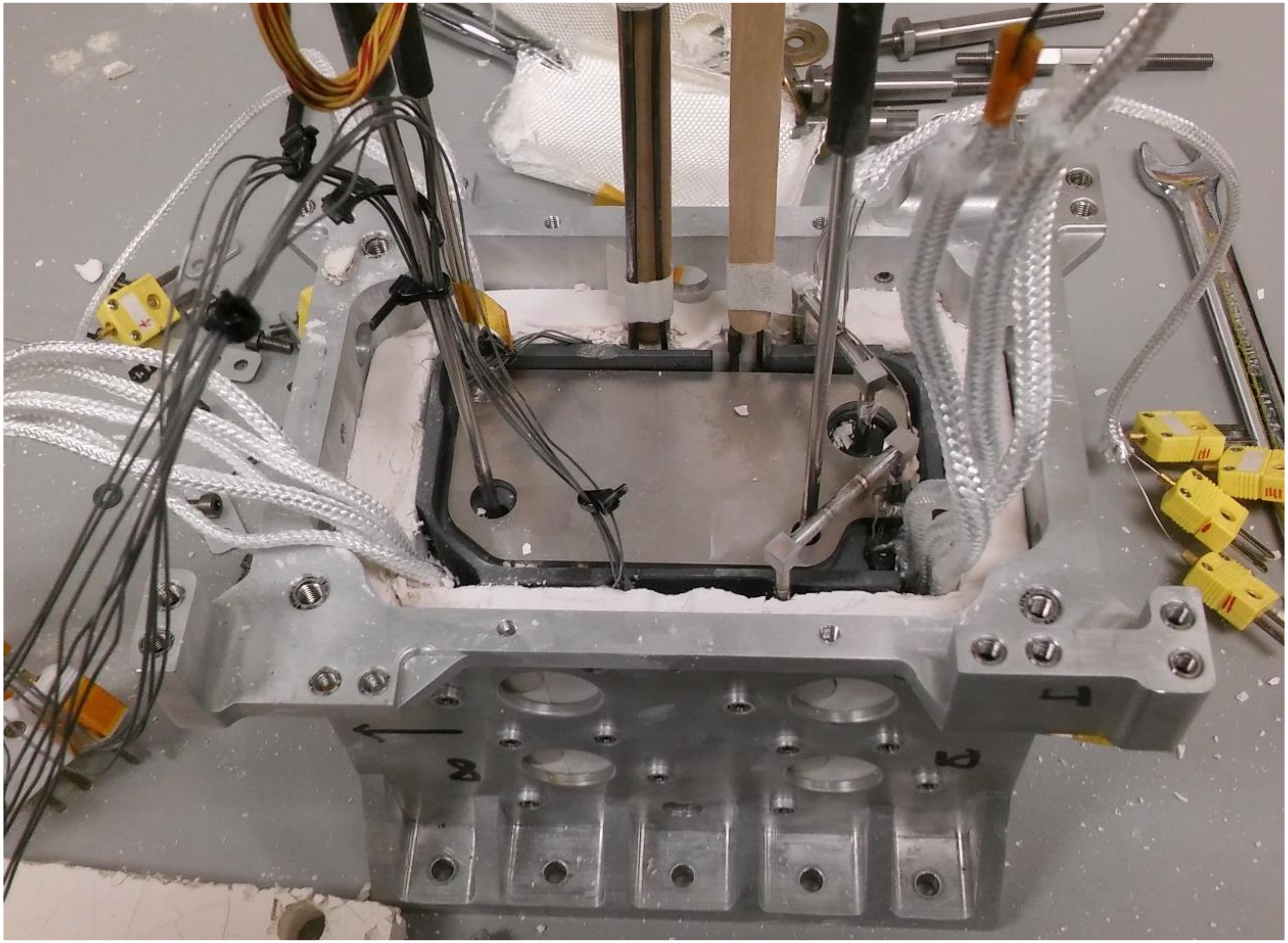


SOXE Assembly

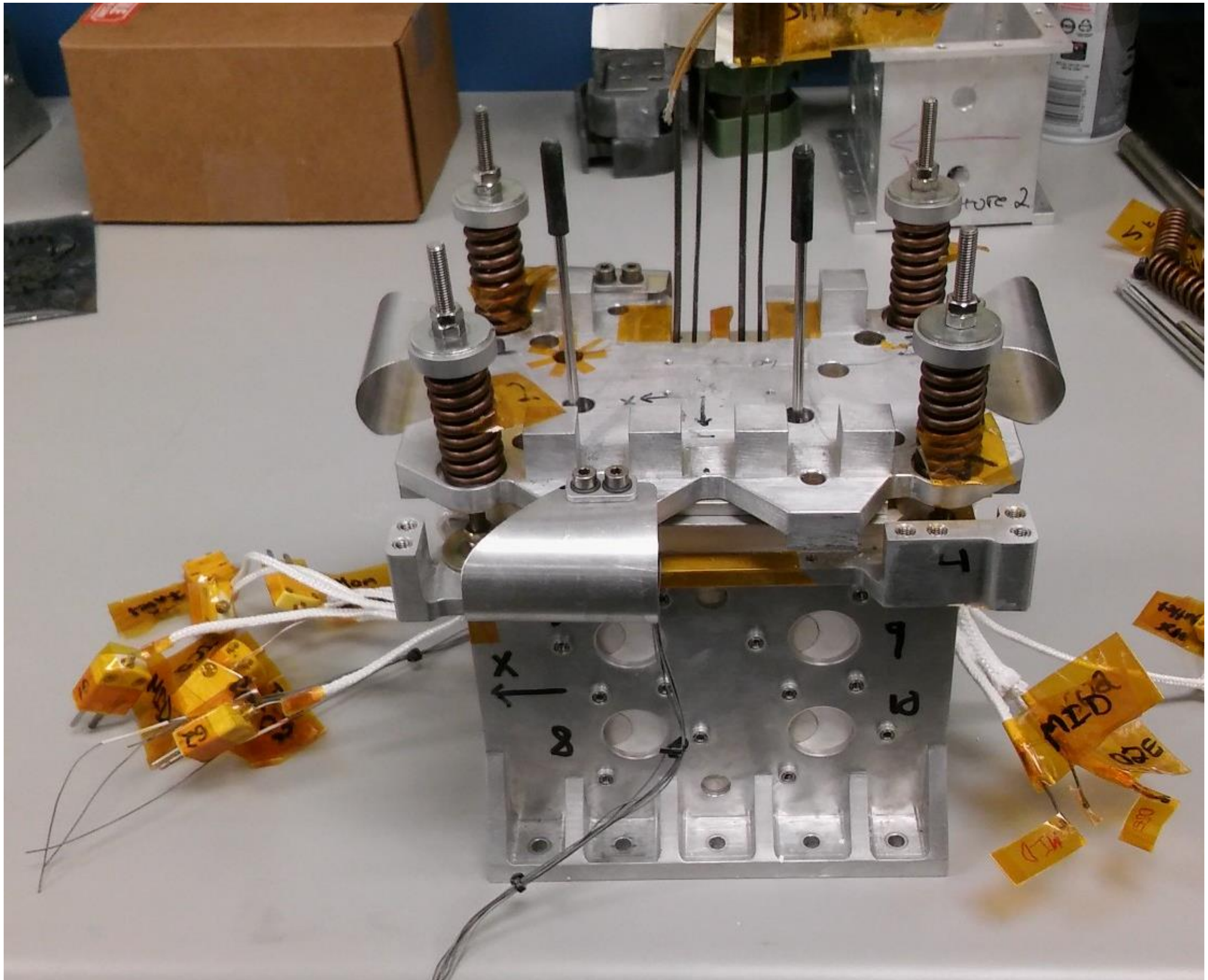


Total mass: ~2.5 kg
Energy required to heat: ~360 W-hr
Power to maintain at 800° C: ~70 W

Prototype SOXE Assembly



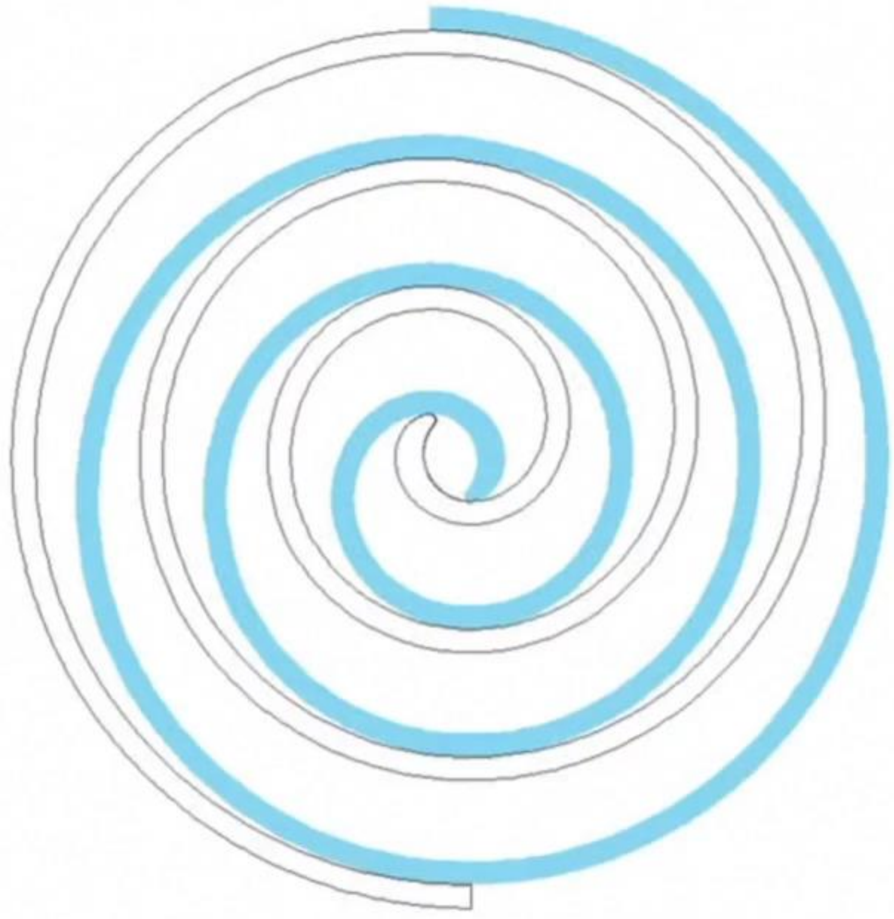
Prototype SOXE Assembly



Gas Delivery – Scroll Compressor

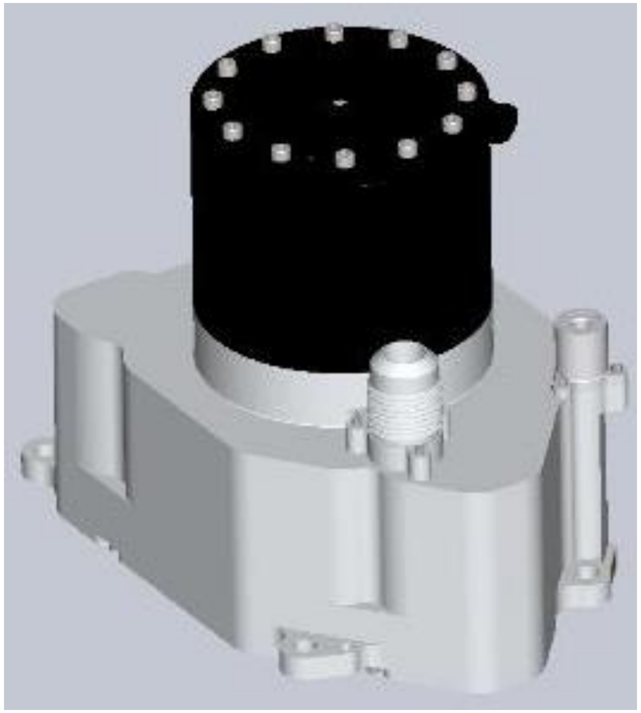
- Scroll pump chosen for real time compression to ~1 bar without intermediate storage.
- Energy efficient, can be scaled at least 10-fold. Lifetime TBD.
- Low-speed (2000-4000 RPM)

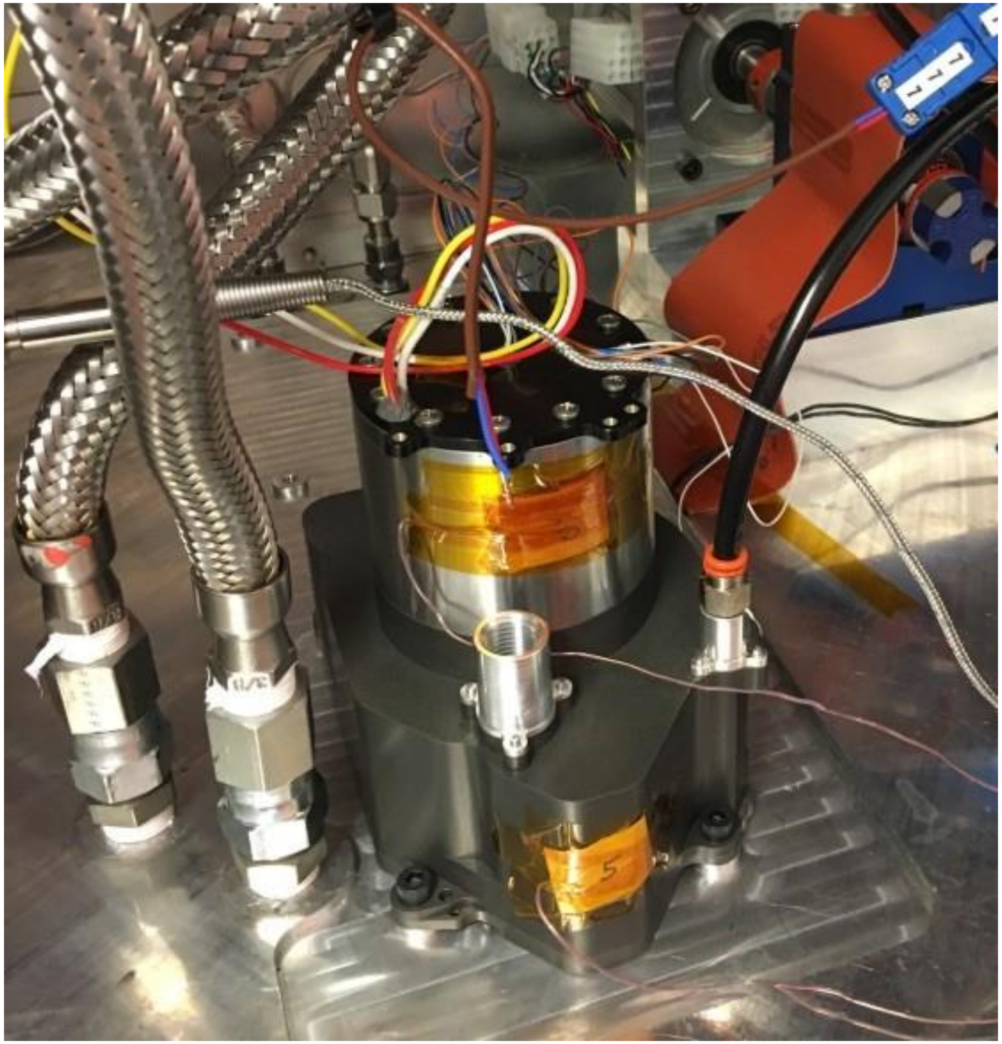
Scroll Compressor operating principle



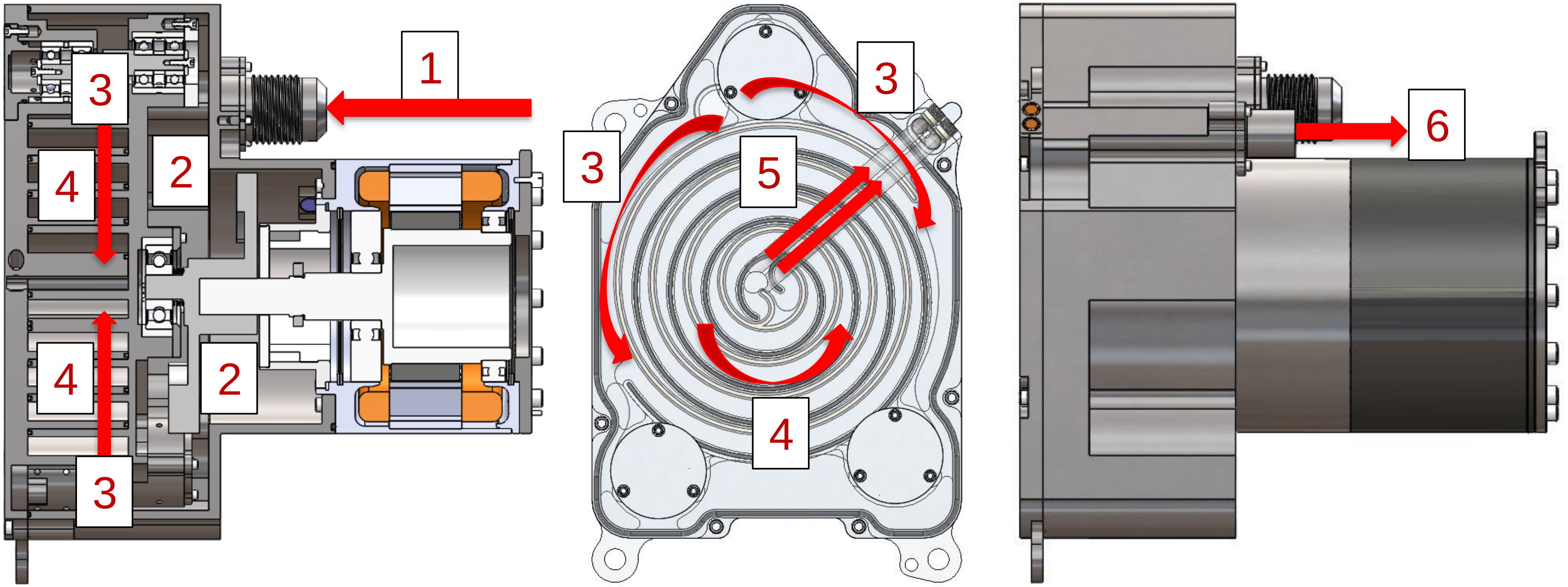
https://www.youtube.com/watch?v=CXmFSb7TIhs

MOXIE Scroll Compressor





MOXIE Scroll Compressor



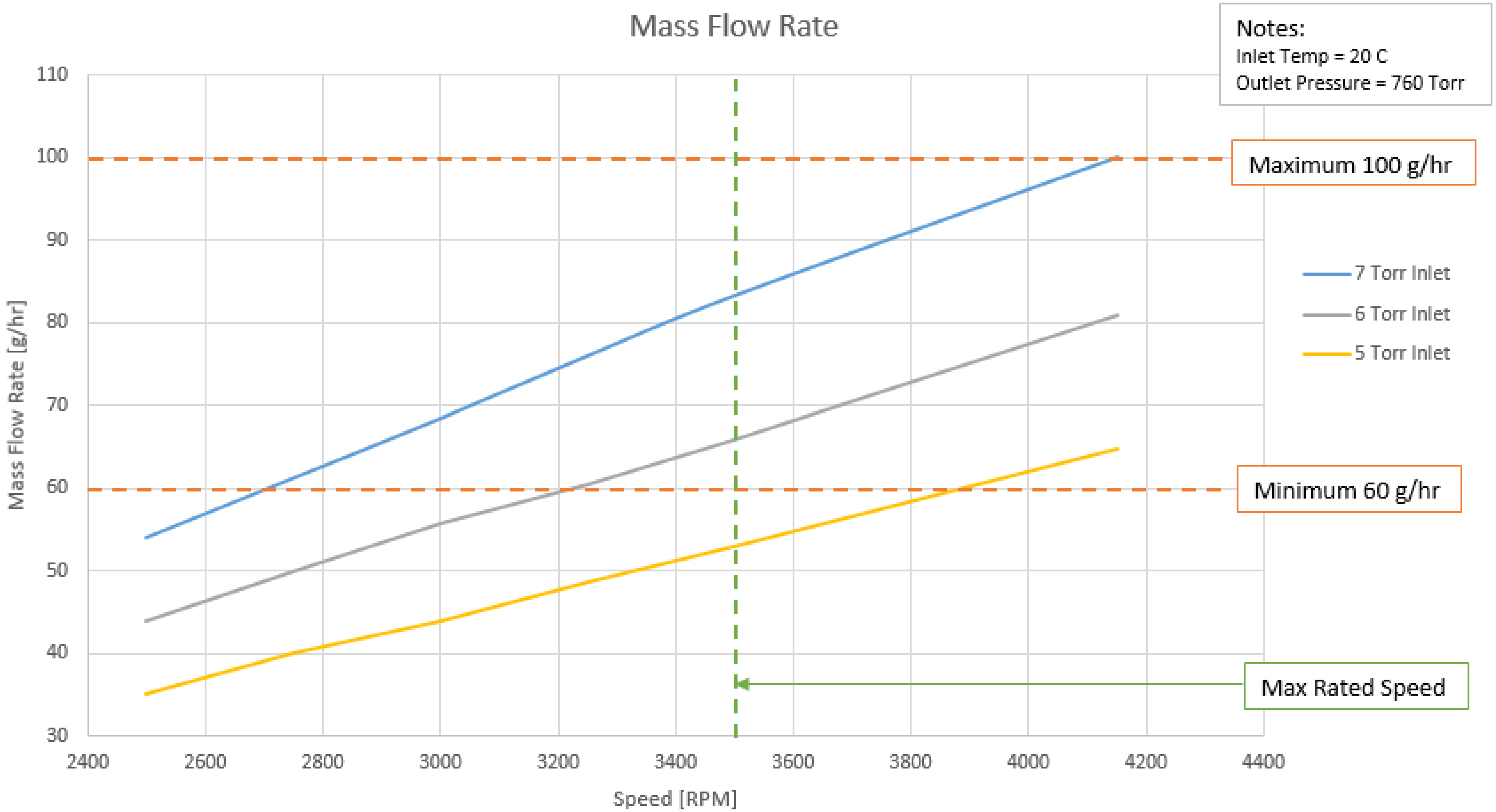
1. Inlet
2. Fill Housing with CO_2
3. CO_2 Enters Scroll Inlets Locations
4. Compression within scrolls
5. Discharge through cross hole
6. Outlet

Performance: 83g/hr for inlet gas P=7 Torr, T= 20°C

P_{in} = 120 W

Mass: ~2kg

MOXIE Scroll Compressor Performance



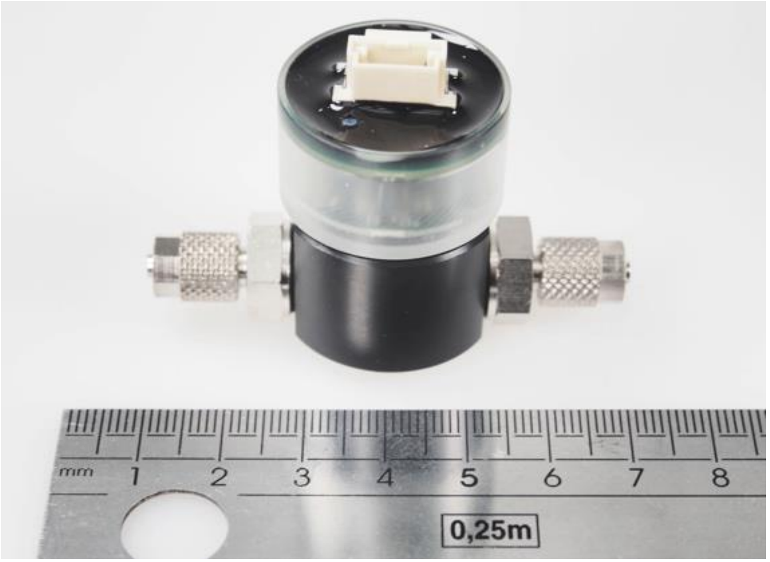
Measured performance: 83g/hr for inlet gas P=7 Torr, T= 20°C

P_{in} = 120 W

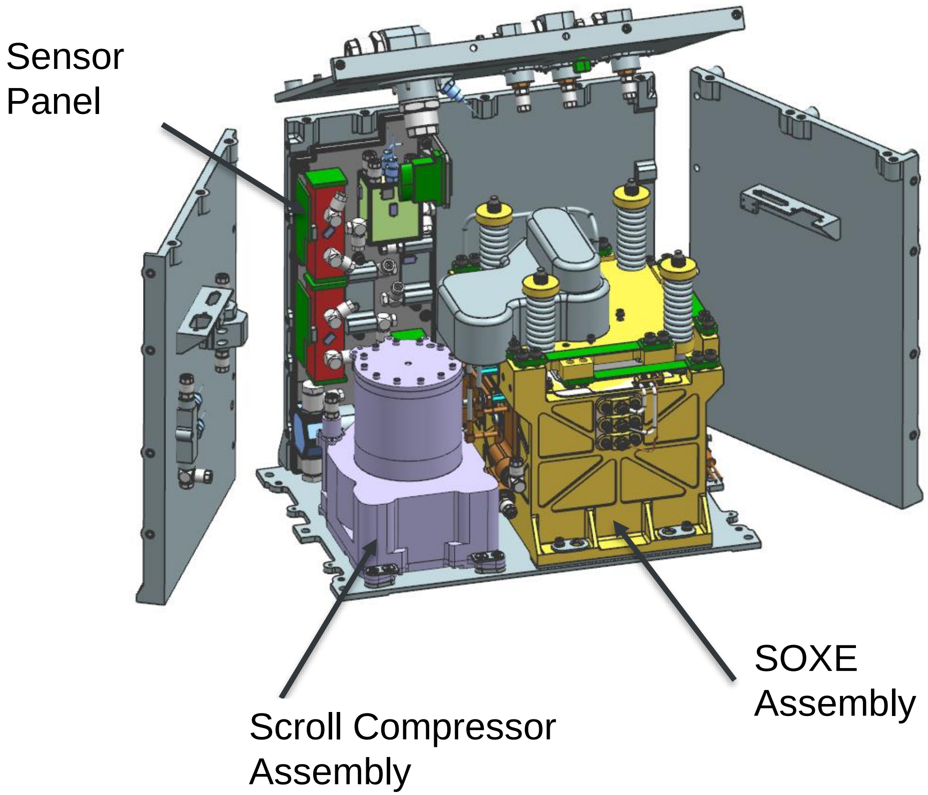
Mass: ~2kg

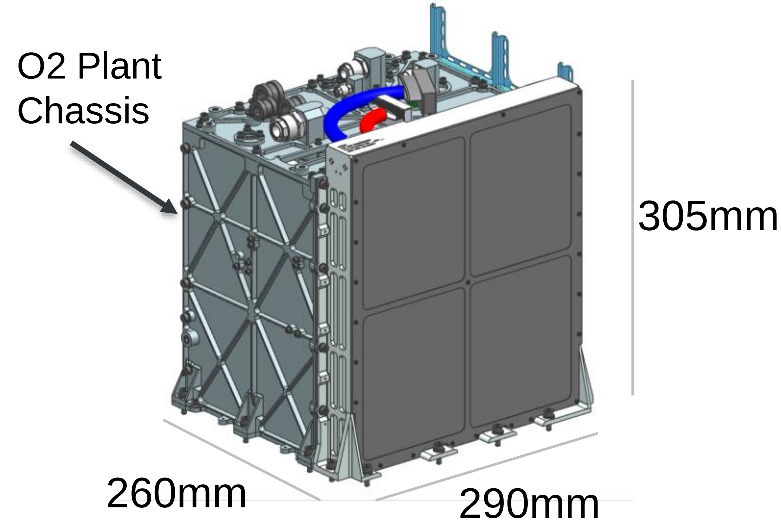
Gas Analysis

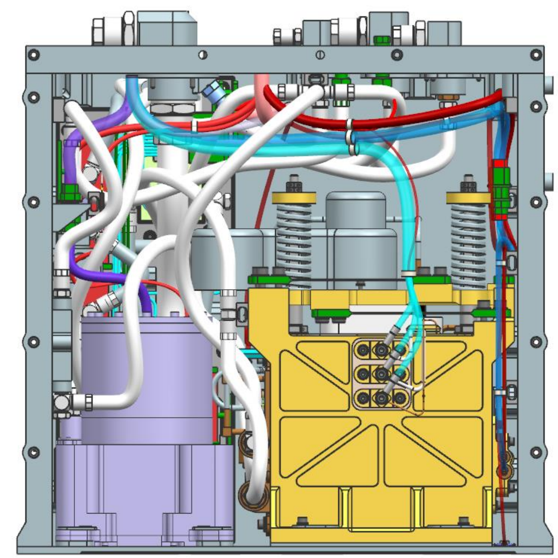
- Anode:
  - Pyroscience O_2 fluorescence sensor (0-100% O_2)
  - smartGAS NDIR CO_2 sensor (0-5% CO_2)
- Cathode
  - smartGAS NDIR CO_2 sensor (0-100%) CO_2
  - smartGAS NDIR CO sensor (0-100%) CO
- Flow meter, pressure sensors, stack current



Packaging

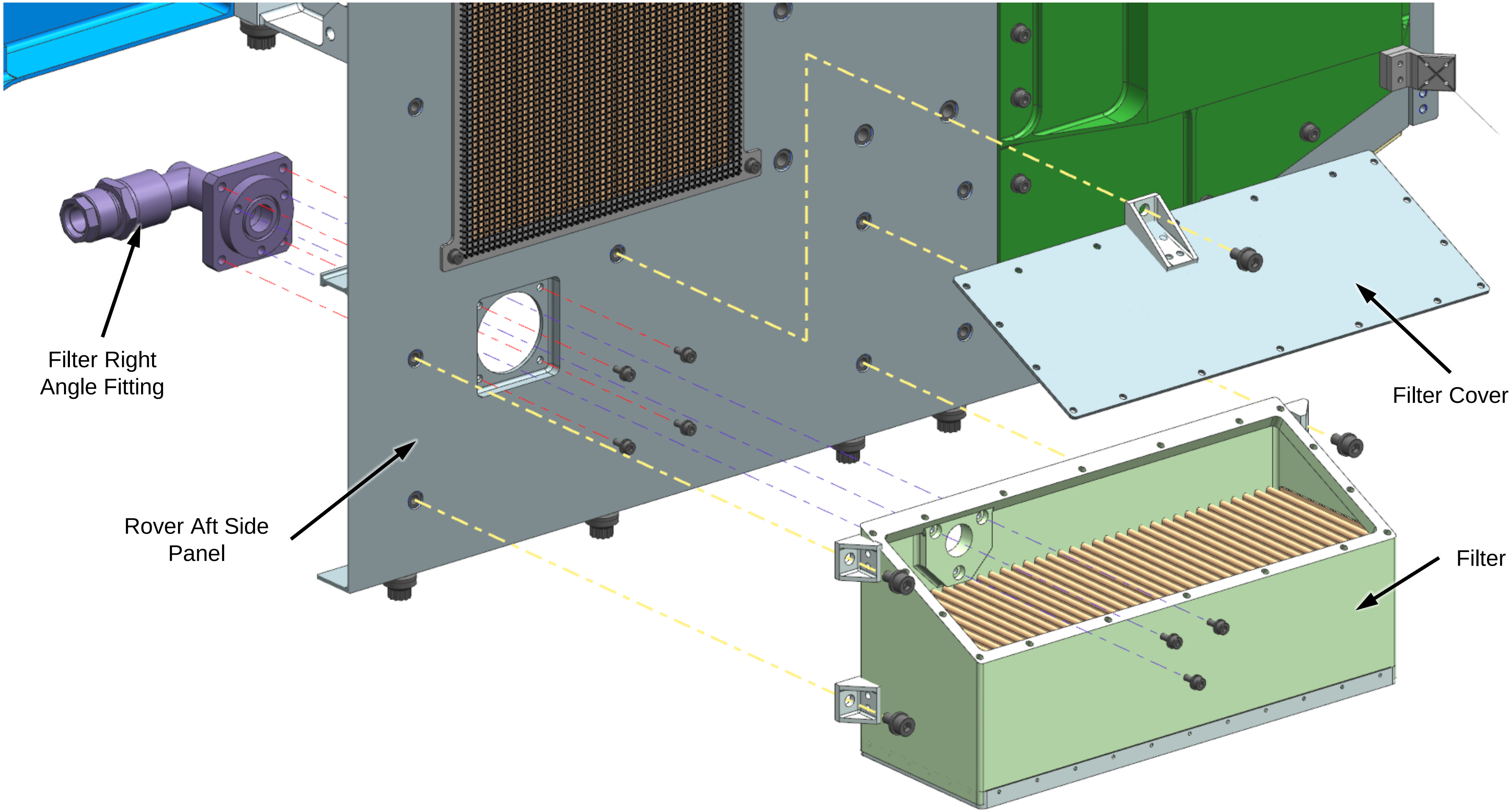




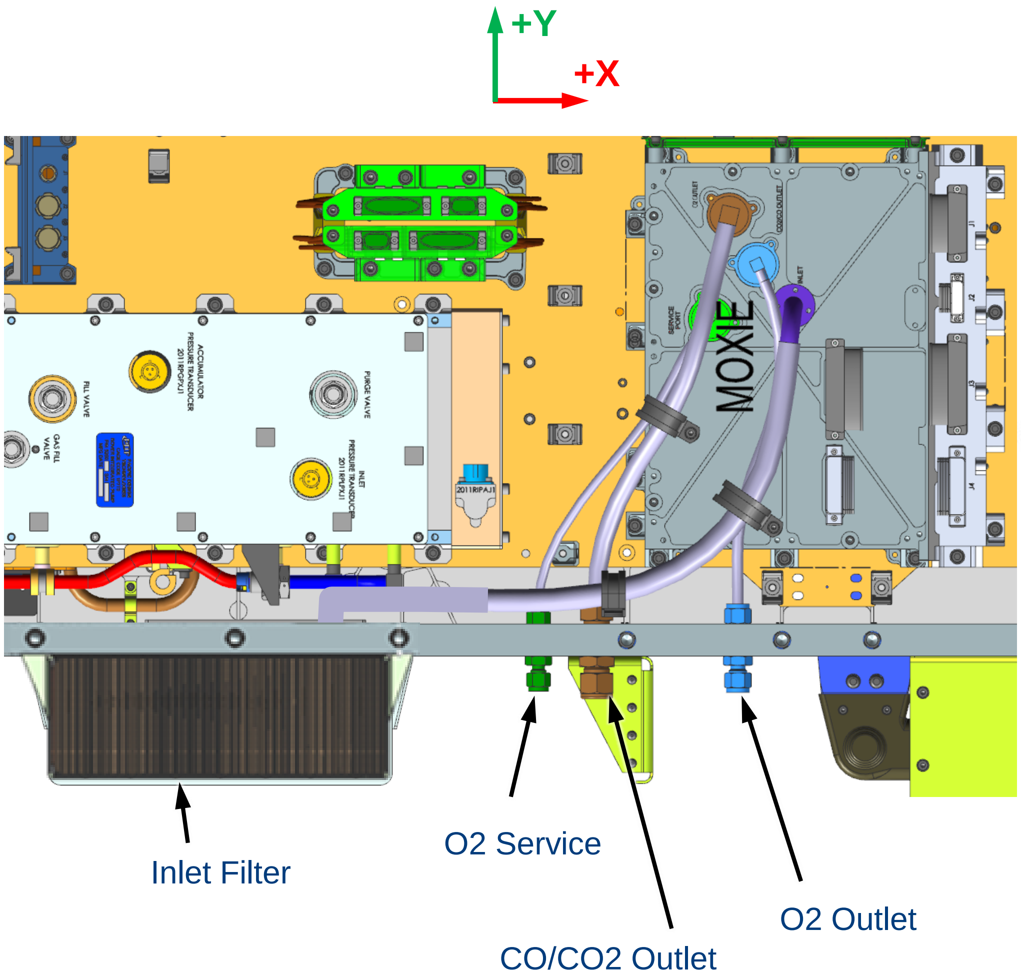


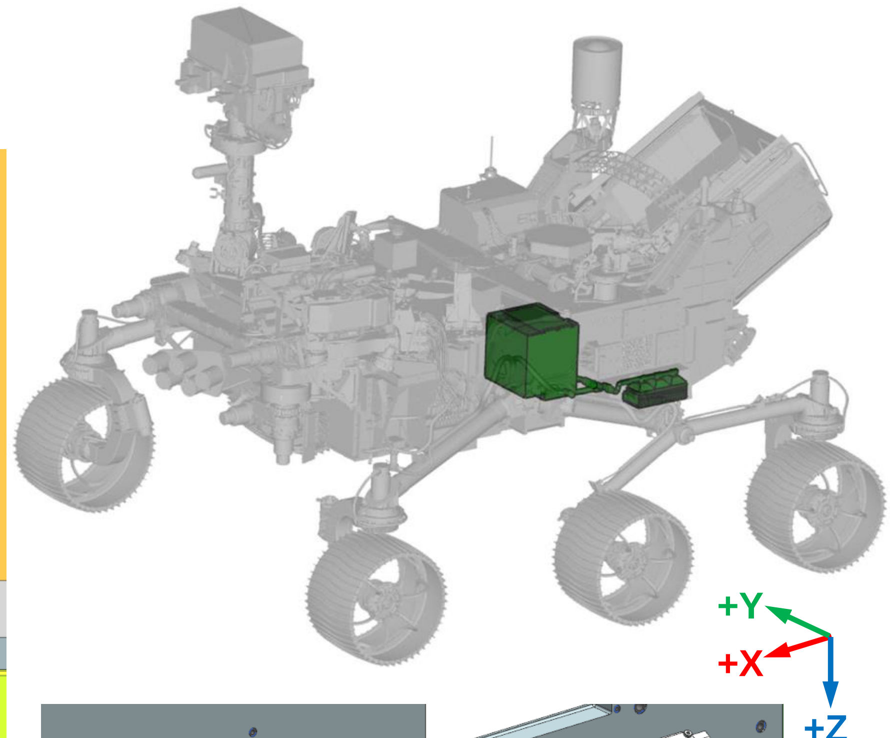
Total mass: ~17 kg
Peak power draw: 300 W
Total energy allocation per run: 1000 W-h

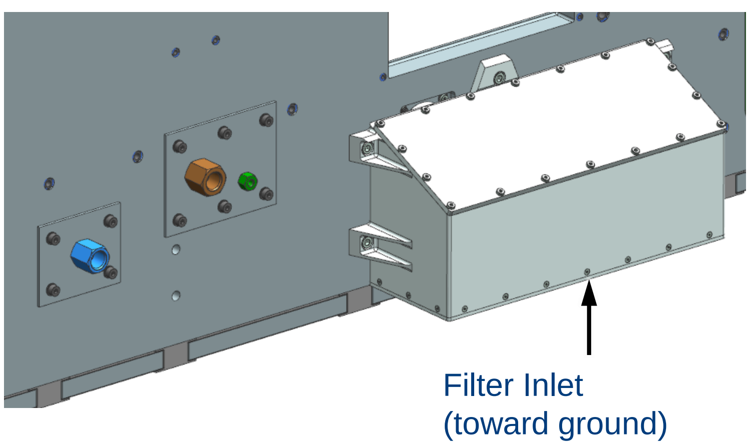
Inlet filter assembly



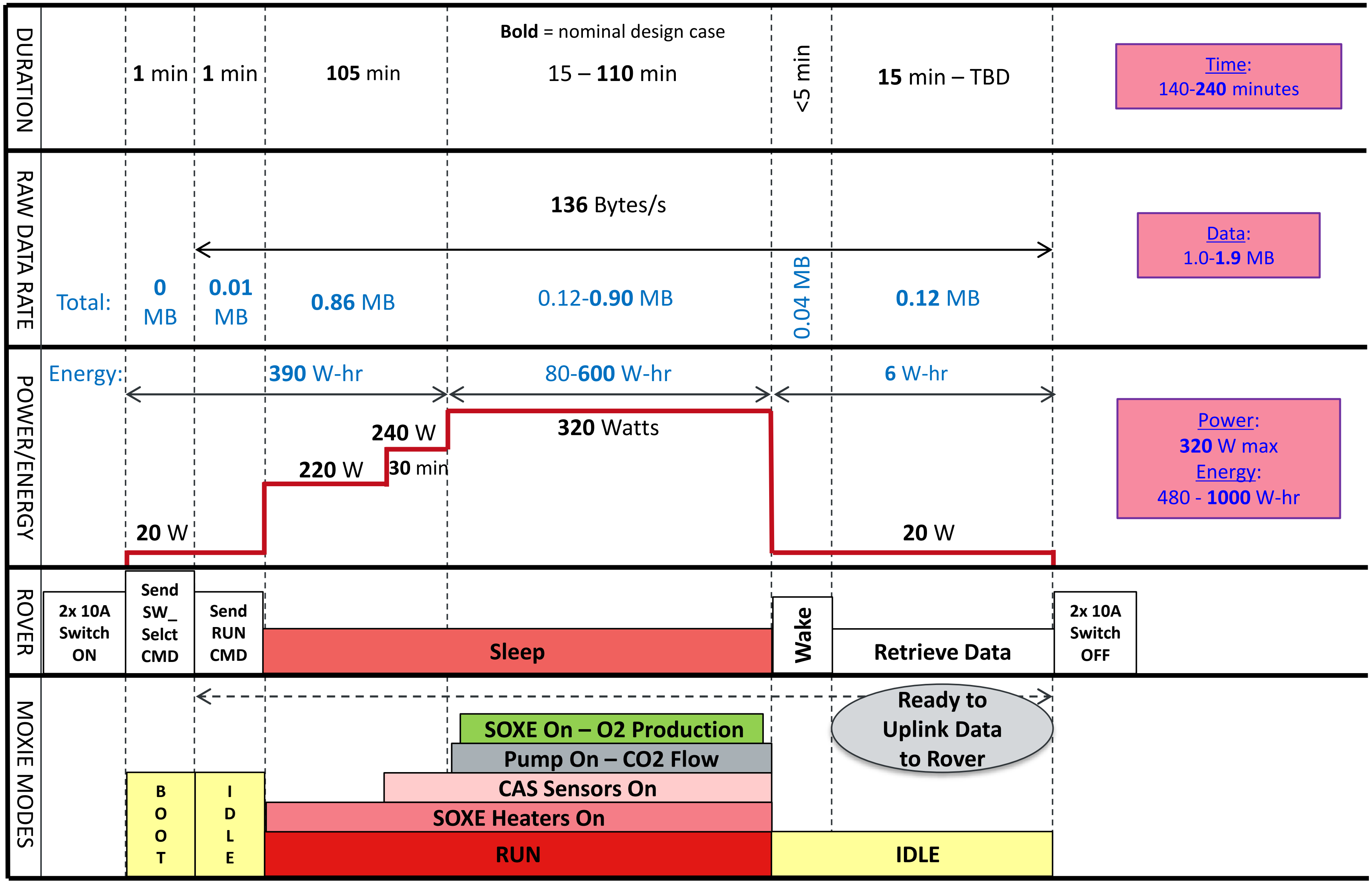
MOXIE on M2020







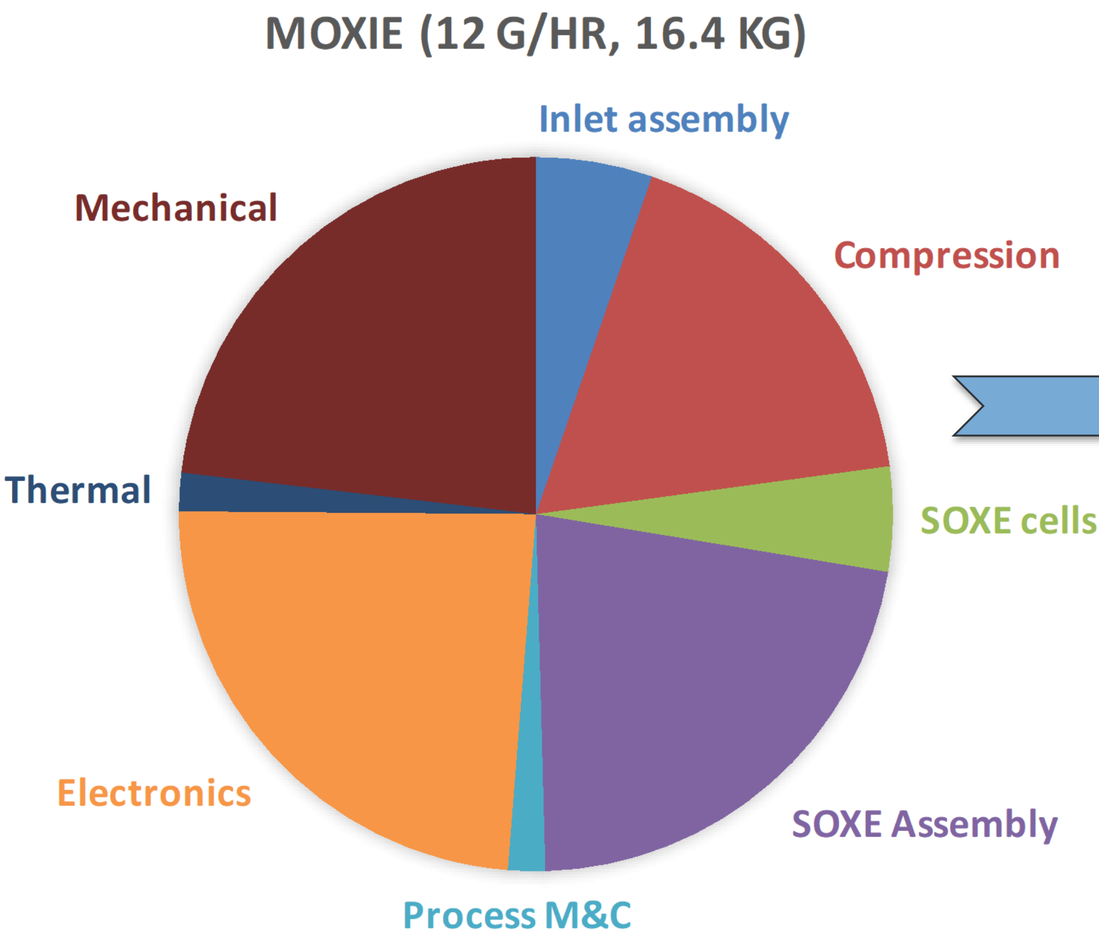
A day in the life of MOXIE



MOXIE Status

- Currently building flight hardware!
- Preparing for integrated system-level testing
- Flight I&T slated to begin in March 2018, delivery to M2020 in October 2018

Looking toward the future: Mass

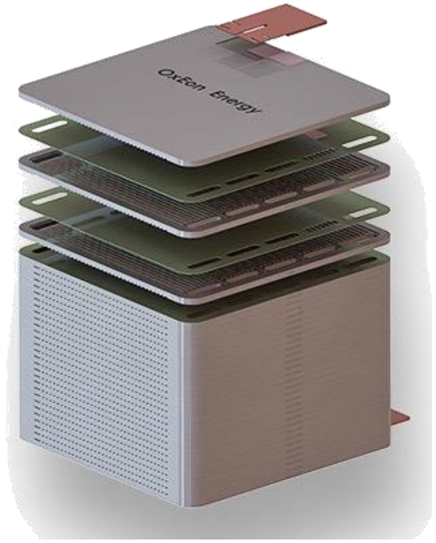


Would scale to 2730 kg at 2 kg/hr!
But…

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Looking toward the future: Mass Scaling

- Scales with production rate R (x167):
  - SOXE cell mass
  - Compressor mass
  - Filter assembly
- Scales with # of modules (x6)
  - Sensors
  - Electronics
- Scales with surface area $R^{2/3}$ (x30)
  - Thermal (insulation, etc.)
  - Structure



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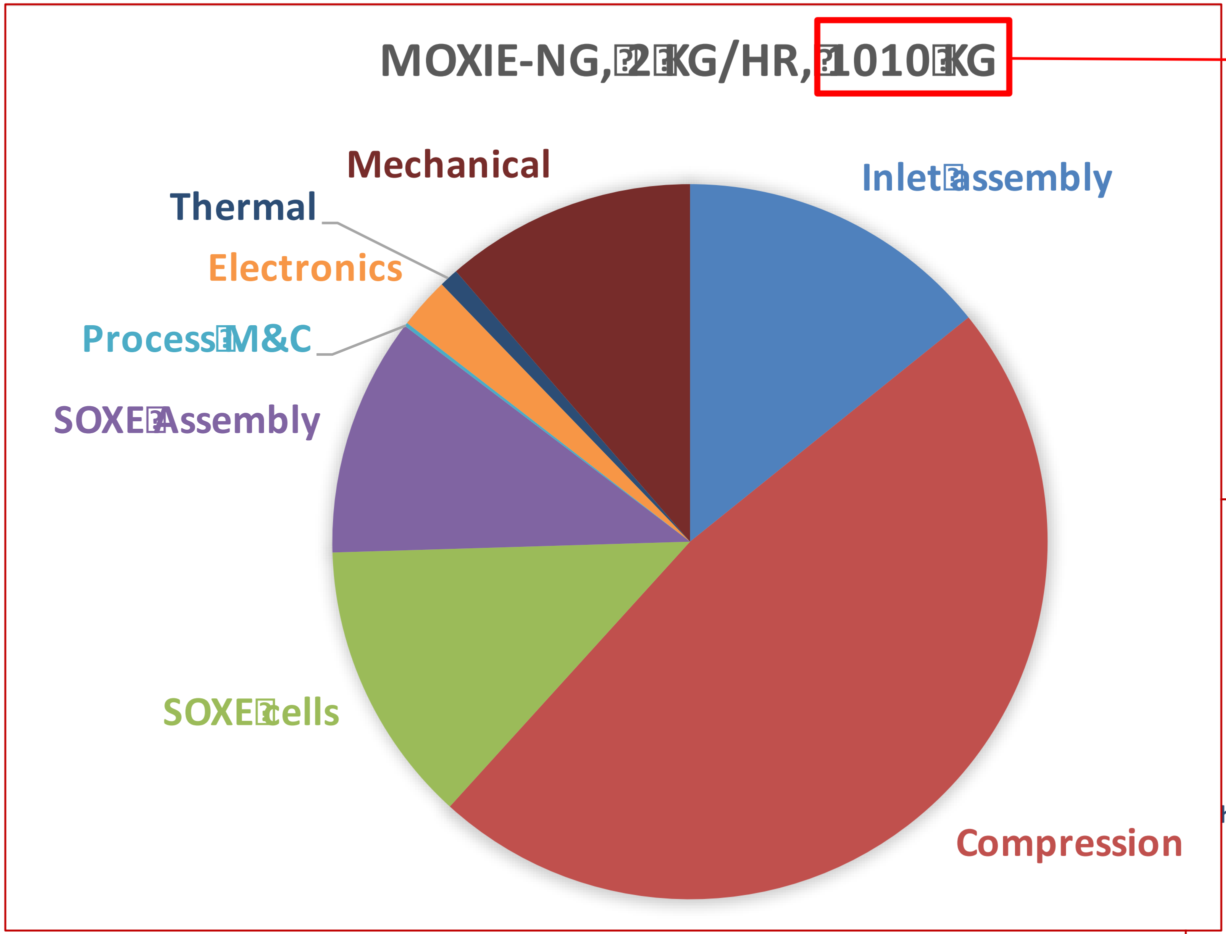
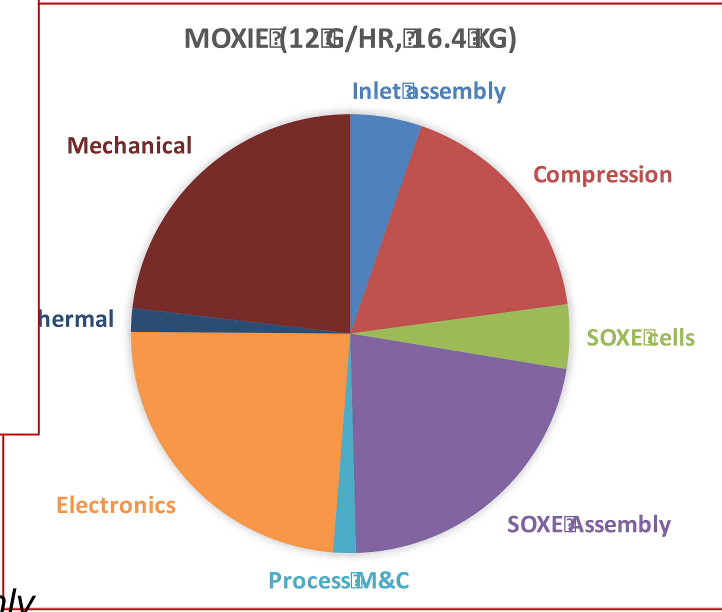
Looking toward the future: Mass

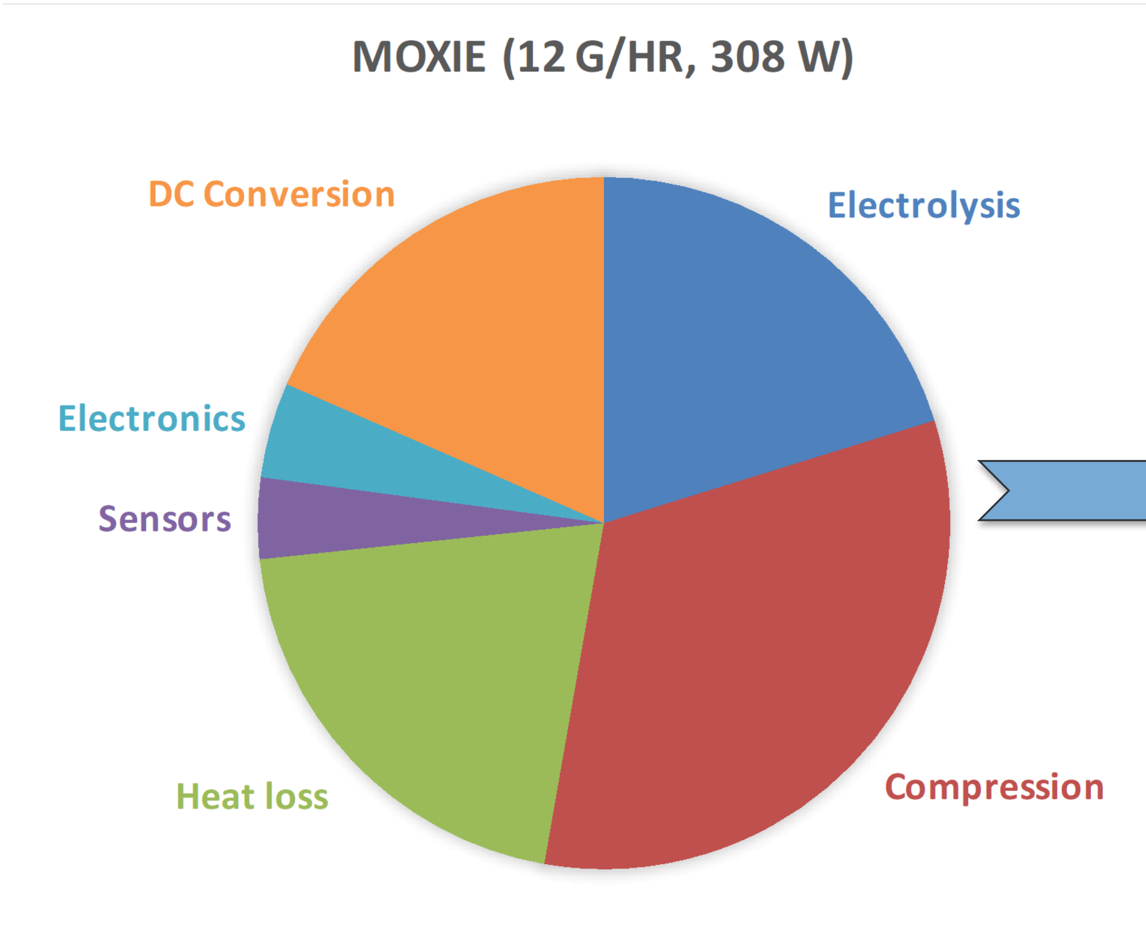


We can land this on Mars



Pre-Decisional Information -- For Planning and Discussion Purposes Only

Looking toward the future: Power



Would scale to 51 kW at 2 kg/hr! But…

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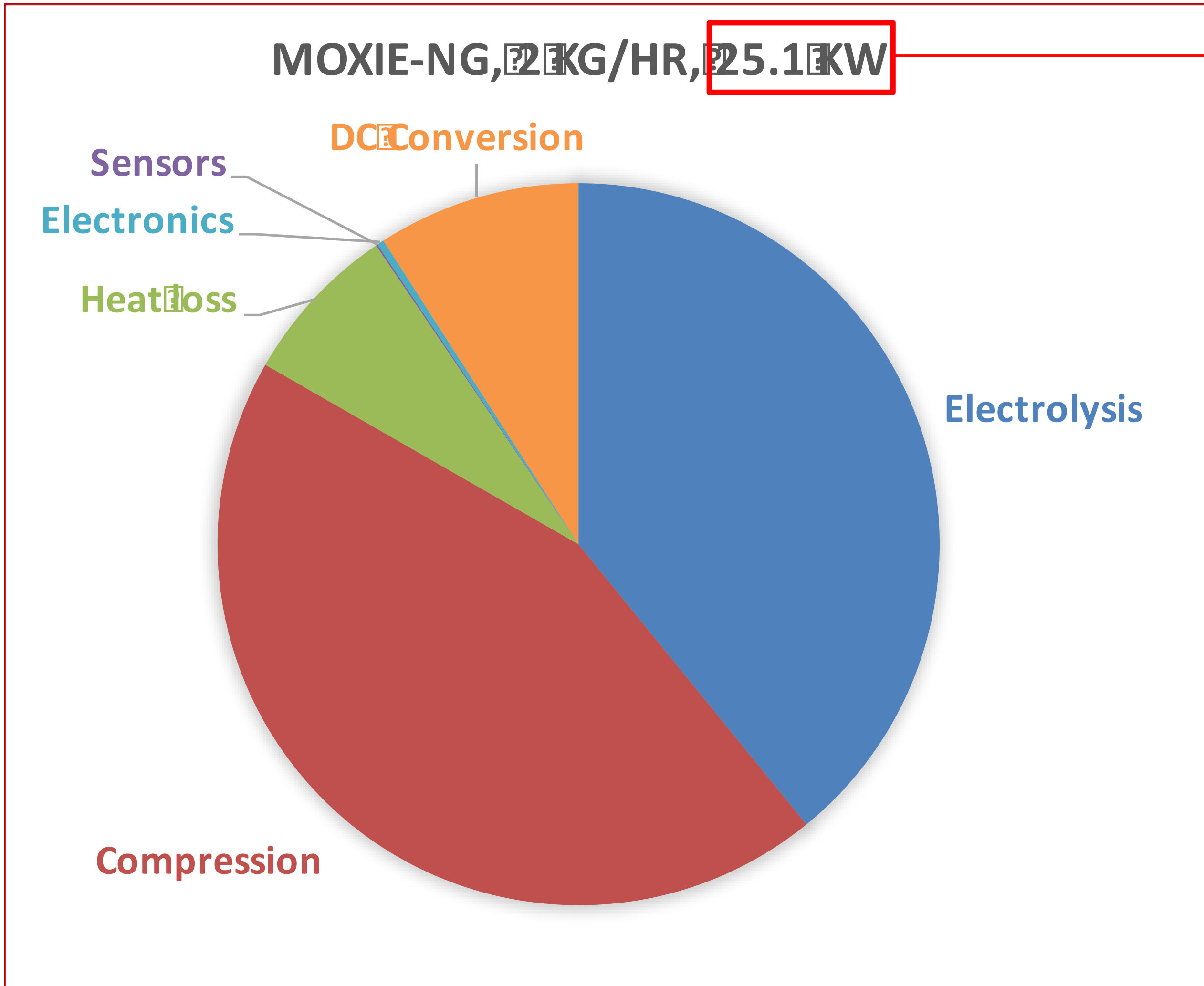
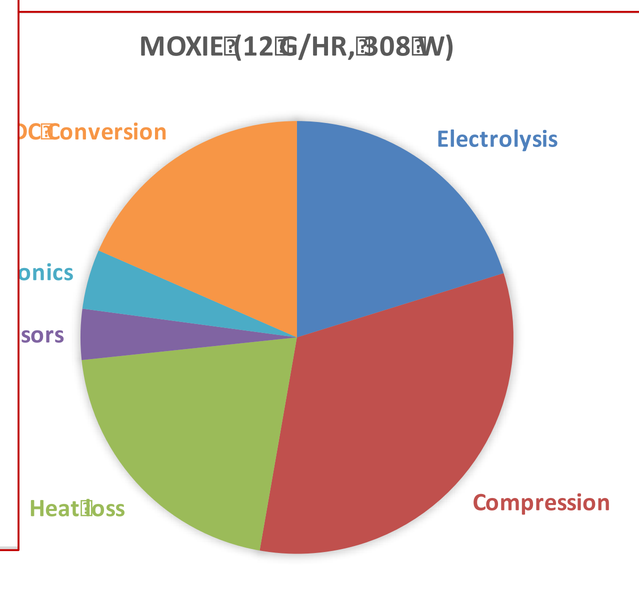
Looking toward the future: Power Scaling

- Scales with production rate R (2000/12 (g/hr) = x167):
  - **Electrolysis (including enthalpy) – rigorously!**
  - Compression
- Scales with # of modules (x6, 334 g/hr each, ~sixty 10x10 cm cells)
  - Sensors
  - Electronics
- Scales with surface area $R^{2/3}$ (x30)
  - SOXE heat loss
- **Expected improvements:**
  - Compression power assumed to be 70% of scaled value
    - Lower elevation (like MSL or VL2) gets you to 75%
    - Reduce output pressure
    - Increase utilization (more SOXE cells or CO_2 recovery)
  - Custom DC converters improve from 83% to 90% efficient
  - Gas pre-heat replaced by heat exchange with exhaust
  - Sensor panel captures heat from, e.g., pump body

Looking toward the future: Power



Would require ~200 m^2 solar array on Mars surface…at peak insolation



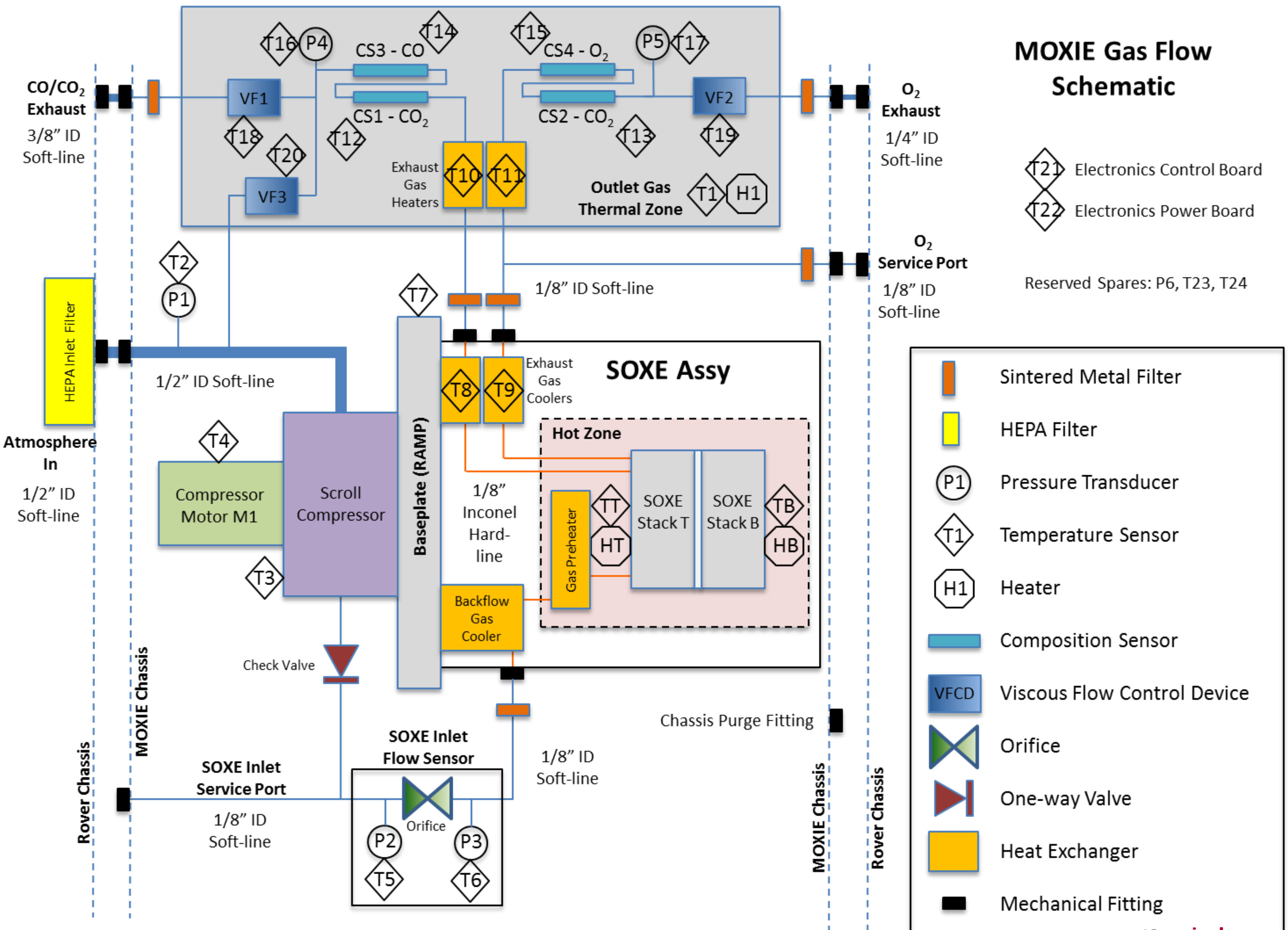
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

Backup

MOXIE Gas Flow Schematic

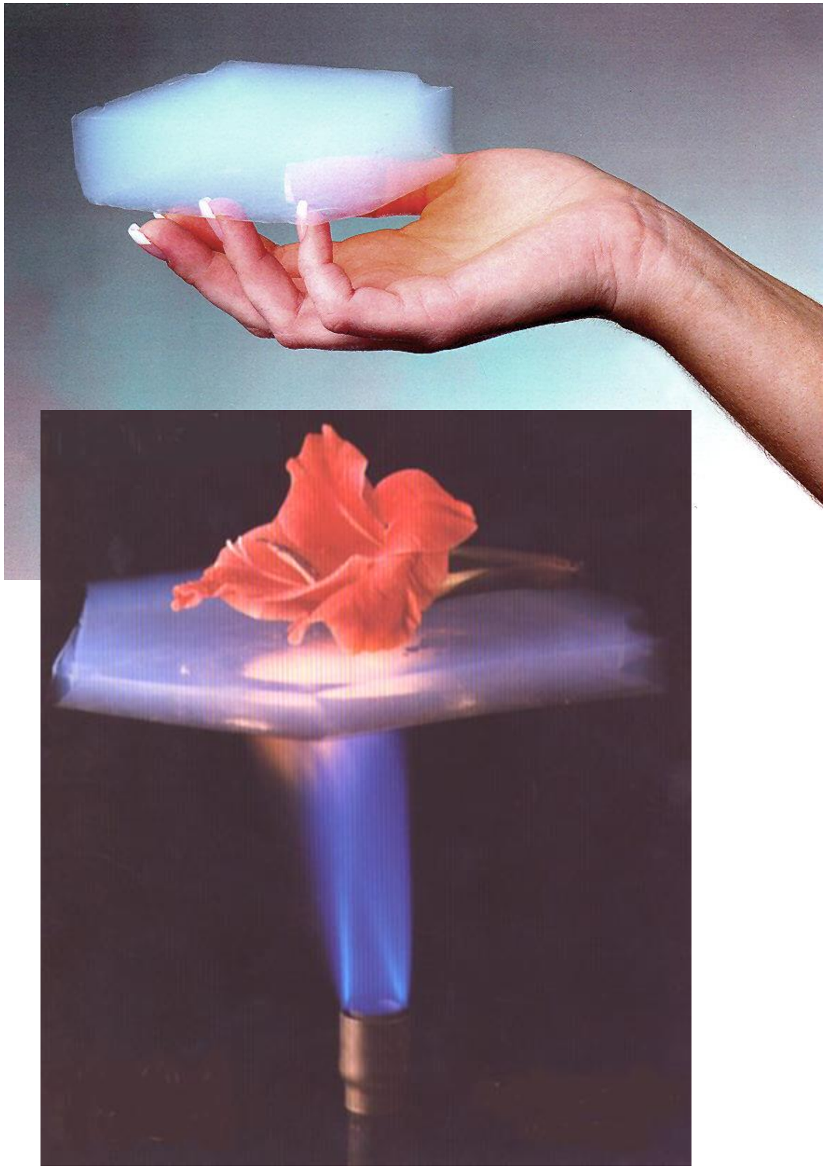


JAJ 12/7/16 Version 21

Aerogel

- Extremely low conductivity, but…
  - Transparent in infrared
  - Brittle

- Solution: Reinforced aerogel composite (JPL-developed)
  - Opacified with TiO_2
  - Reinforced with silica fibers
  - Not as good thermally, but much easier to work with!



Aerogel

Compression power